MANAGEMENT OF REGIONAL RESILIENCE THROUGH GOVERNANCE OF INFRASTRUCTURE OPERATIONAL RISK

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Abstract

In this paper the notion of urban infrastructure resilience, expressed verbally and strictly in conditional probability terms, is formulated. It is then used to formulate several most important features of a smart city. This multidisciplinary and multifaceted approach is used to explain the concept of quantitative resilience in urban design, operation, managing urban risk and mitigating of the consequences of a natural or industrial disaster. The super urgent problem is formulated on how to connect the physical and spatial (core) resiliencies with the functional, organizational, economic and social resiliencies.

Keywords: urban resiliencies, interdependent critical infrastructures, regional risk, potentially dangerous objects, systems of systems, average life expectancy, life quality index, carbon foot print.

I. Introduction

Currently, the concept of resilience emerged as a central theme of industrial and urban development (there are more than 120 definitions of resilience, most of them are qualitative). It is capable of serving as the basis and tool for solving the most urgent issues of modern civilization, including strategic investments by leading development institutions and humanitarian communities around the world. Despite the importance of critical infrastructures and systems and expected growth of future climatic hazards, relatively few studies have addressed these issues and no methodology for the analysis of such an impact has ever reached a general consensus. As of now, it seems (to our knowledge) that there is no quantitative definition of resilience and strategic preparedness to which a majority would subscribe.

Cities are conglomerates where the majority of humanity lives. In the last century and decades urban ecosystems have evolved from simple clusters of buildings to extremely complex systems of systems (vast networks of services) strongly interdependent on one another. In order to become a resilient city, it is necessary that different stakeholders find a way to compromise through thoughtful governance, and carry out operational procedures of complex or territorial systems in groups.

The quantitative and qualitative analysis of resilience as related to urban infrastructures takes its roots from the notion and concept of industrial resilience [1–4]. In this paper the urban infrastructure resilience is defined both verbally and strictly in conditional probabilistic terms, as all the parameters which describe resilience quantitatively, are random. The conditionality of the resilience probabilities is due to the probabilistic and uncertain/fuzzy nature of the impact, and of the financial, social and other restrictions on the critical infrastructure, for which the resilience is assessed.

Resilience is considered as a probability vector, which components include the physical, environmental, and spatial resilience, as well as functional, organizational, economic and social resilience. Each component of the resilience vector can be considered as a partial resilience as related to different aspects of the considered type of resilience. The physical and spatial resilience of a system of critical infrastructures is defined through its reliability and operational risk.

It is possible to implement a multidisciplinary and multifaceted approach to urban critical and strategic infrastructures of different nature, using the above novel concept of quantitative resilience in design, operation and mitigation of the consequences of an urban disaster.

The paper describes verbally and quantitatively how to manage urban risk by exercising governance which balances technological innovation, economic competitiveness, environmental protection and social flourishing using such regional criteria as resilience, life expectance, life quality index, carbon foot print and regional entropy.

The overarching idea of this research is that *human life time is the only true and universal measure of things*. Probably, the first who formulated this was Henry David Thoreau, who in his novel «Walden», 1852, wrote: «The cost of a thing is the amount of what I will call life which is required to be exchanged for it, immediately or in the long run».

Before addressing these issues, it is necessary to introduce several definitions and notions, which follow. Main sources of regional risk are: nature; systems of interdependent critical infrastructures (SICIs); people (population of the region, and vandals). Critical infrastructure is any large localized or, more often, distributed across a specific territory multicomponent geotechnical man-machine-environment system, which consists of many potentially dangerous objects (PDOs) and groups of people, who operate and/or live near these objects. Practically, the CIs are PDOs, which *cannot function without each other* when producing some sellable product or/and service, *and hence, are interdependent*. The ICI must operate effectively, meet the standards of well-being and safety for the population, and provide environmental sustainability of the region.

II. Short history of the resilience concept

In Russian language the word for resilience (*zhivuchest*) has as its root the Russian word *zhivoy* (*alive*) and means capacity of an object (*animate* or *inanimate*) to continue, *without interruption*, its functioning (staying «*alive*»), while being damaged by extreme loads, forces and/or influences. The Russian Dictionaries define *zhivuchest* as human longevity, or as capability for robust performance of a ship under the influence of wind, waves, fire, and enemy artillery. It, obviously, contains in itself the notion of *endurance*. The English word resilience originated from *resilire*, the Latin word meaning skip *backward* or *rebound*. In the Western world the concept of *resilience* as a common notion was adopted early 17-th century and, by the end of that century, the concept evolved to mean the *ability to react after (not during) a shock*.

It seems that Admiral O.S. Makarov of Russian Navy was the first who introduced, way back in 1894, the notion of infrastructure *resilience* in reference to the ability of battle ships (as elements of the war infrastructure) *to continue their effective performance* under artillery fire and subsequent damage [5]. Seven years later, in 1901 the Charpy impact V-notch high strain-rate test, that determines the amount of energy absorbed by a material during fracture, was standardized, and its *resilience* was defined as the capacity of the test material to absorb an impact. So the modern concept of resilience comes from the metal industry, in which it is defined as the capacity of steel to withstand an impact, to maintain its shape, and to recover fast after receiving an impact. The notion of resilience was then gradually used in defining the behavior of different mechanical systems (beams, trusses, shell-like structures, bridges, as well as industrial and military vehicles and machines, etc.).

Fast forward, during the 20-th century, the term *resilience* penetrated many branches of science and is now widely used in physics, psychology, anthropology, economy, and ecology. During this period resilience is linked to such concepts as elasticity, longevity, durability and persistence, ability to adapt and rebound.

The notion of resilience spread, starting from 1936, to social psychology, when describing human elasticity, good mood, resourcefulness and spirit. G. Vickers stated [5] (1965) that a system is resilient if it's able to survive despite being beaten by shocks, hazards, or distress from internal or external turbulences. In the seventies, the idea of resilience becomes present in the ecology field, where resilience is defined as a way to measure the persistence of a system, its capacity to absorb turbulences, and its ability to keep the healthy relationships between the population and the different layers of the system [6]. At the end of the last century, the idea of resilience was utilized in economics, where it was understood as the capacity to stay on course, keep a juridical entity or business going and maintaining stability in a volatile environment. In the early years of the 21-st century, the resilience concept has been embraced by management, organizational, FEMA and HSA (when dealing with incidents, catastrophes and terrorist attacks), safety engineering and computing. The concept of resilience is also becoming more and more relevant in climate change and sociology [7].

III. Urban resilience

Currently, cities contain in their bowels 50+ % of the world's population. With rural population decreasing, the global population growth will continue in urban areas. Cities attract people because of the quality of work, services, communications, security and social relations, etc. Although some of the living conditions in cities can be worse than in rural areas, but, in general, the urban quality of life is overwhelmingly better that rural existence.

Cities can be classified as: 1) large, medium and small; 2) metropolitan, urban, semi-urban and rural; 3) consolidated and developmental. They can belong to the four existing global environments – rich, modest, poor and miserable worlds. Any city can be classified by these three characteristic factors and the four world types in which it is located.

Cities grow at an ever increasing speed, and are currently subjected to a multitude of pressures, out of which the following four are of greatest concern: 1) evolution of technology and globalization at a neck breaking pace; 2) fast socioeconomic changes; 3) obvious climate change; 4) the growing needs of demanding citizens, due to a combination of the above elements.

All of the above creates new threats and the necessity to protect citizens from these threats. They could be effectively mitigated by the novel concept of *urban resilience*. According to the Rockefeller Foundation [8]: «*Urban Resilience is the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow, no matter what kinds of chronic stresses and acute shocks they experience, and even transform when conditions require it.*» The European Commission defines resilience (in general) as «*the ability of … a community, a country or a region to withstand, adapt, and quickly recover from stresses and shocks such as drought, violence, conflict or natural disaster*». Resilient systems refer to those institutions, cities or states that have the ability to reconstruct and to recover, using the right tools, assets and skills to deal with impacts and resist, absorb and adapt. The challenge here actually is how to manage these risks effectively, and how to transform a generic resilience concept into a tailored resilience of a specific infrastructure or a system.

The world community adapted this idea in economics, social issues, and *urban contexts* when overcoming disaster and climate changes. The scale of urban risk is increasing due to the increase of the number of people living in cities. Risk is also increasingly unpredictable, due to the complexity of city's systems of systems (SoS) and the uncertainty associated with natural disasters, industrial catastrophes and climate change.

Consequences of climate change are increasingly dangerous for citizens and urban network services. Related events can cause tremendous economic impacts and losses for cities, due to their population density and asset concentration. Global economic losses from natural disasters have averaged almost $200 billion (1998) per year over the past decade, up from just $50 billion per year in the 1980s, according to the World Bank and Munich Re, the world's largest reinsurer. Total costs sum up to $3.8 trillion from 1980 to 2012. Three-quarters of this total was due to extreme weather-related events. According to some analysis [10], the economic impacts of these types of emergencies can be reduced by up to 10 %, using appropriate diagnostics, monitoring, maintenance and decision making tools. Environmental risks (extreme weather and climate change) outnumber economic (unemployment, underemployment or fiscal crises) risks, according to the latest report of the World Economic Forum (WEF).

The network of urban services is becoming more and more complex due to a high degree of interconnection between them and the evolution of the technology and requirements/demands of the citizens. Confusion may arise when dealing with the enormous databases (Big Data) that are created by the new information technology. All this implies that failure of one specific service endangers the ability of many other services to provide service, unleashing domino effects that spread far from the initial event. Another threat lies in that contemporary cities experience a decrease of city budgets and outsource the services to minimize costs. This leads to pronounced deficit of coordination and communication between the networks of urban services.

The total number of cities around the world interested in urban resilience is hard to estimate, but currently there are 1520 emerging cities associated to the UNISDR program *Making Cities Resilient* (mostly from Central and South America, Balkan Europe, India and Far East), a hundred cities in the Rockefeller Foundation *100 Resilient Cities Program*, located in North America and Europe, including such metropolitan cities like New York, London, Paris, Rome, and Barcelona [8]. This means that modern world wide urban society centers also on metropolitan regions, and the security, resilience and viability of metropolises also relies on their *critical infrastructures*, core public services and economic bases.

I. Brief verbal description of urban resilience

The definition of urban resilience was given above. Resilience is the driver and, simultaneously, a precious quality of *sustainable* urban development. Considering a city as a system of systems (SoS), resilience recognizes all of them as dynamic and complex systems that have to continuously adapt to various challenges of *stochastic, probabilistic, uncertain, or vague character* in an integrated and holistic manner. Each part of these systems has an inherent reliance on all the other parts.

In general, factors that influence city resilience include: the range and severity of hazards; the risk to life, limb and property; the vulnerability and exposure of human, social, and environmental systems, and the degree of (strategic) preparedness of the physical and the governance systems to any Natural or urban and industrial shocks and stressors and their consequences during an incident, accident or catastrophe. The resilience concept adopts a multiple hazards approach, considering resilience against all types of plausible hazards, and refers not only to reducing risks and damages from disasters (i.e. loss of lives, limbs and assets), but also the ability to quickly recover back to the pre-shock stable state. Using resilience concept permits correct placing of strategic investments by leading development institutions and humanitarian communities around the world.

II. The essence and components of urban resilience

The essence and components of urban resilience consists of working to: 1) prevent any potential threat; 2) withstand any impact caused; 3) react to the crises derived from the impact; 4) recover the city's functionalities; 5) learn from the experience.

Urban resilience is based on humanitarian, vertical-operational and cross-cutting approaches. The *humanitarian approach* focuses on resilience of *cities*, regions and countries, taking into account how they are able to deal with industrial and natural disasters, climate and social changes, and how these impacts may affect the welfare of citizens in terms of life expectancy, life quality index (LQI), etc., and how the sustainability of the environment is affected. *The cross-cutting approach* to resilience implementation holistically tackles functioning of a city in a comprehensively manner, observing the city strategically as an ecosystem of interdependent urban services. The v*ertical-operational approach* studies the complex anatomy of a city, and its different elements (society – individuals, groups of people, government, etc.); services and infrastructures that contribute to the welfare of citizens, and the interactions between the society and its services and infrastructures.

Urban resilience consists of four phases: 1) *Operating* – the ability to withstand, respond or recover after an impact; 2) *Planning* – simulate incident and disaster events and decide accordingly; 3) *Improving* – learning from the experience in order to correct and project current strategies to ensure city continuity in the event of an impact; 4) *Preventing* – foresee potential hazards before they happen by identifying risks and diagnosing the environment.

The four main components of urban resilience are: industrial disaster and climate resilience, economic resilience, social resilience and urban resilience. All this is achieved when the city becomes smart. There are two competing concepts of Smart Cities. The first concept is used to equip the infrastructures and the services for the optimal management of the city as the path to reach a Resilient City. In the second concept the optimal management of a city goes through already resilient network of services and infrastructures equipped with smart technology to create a Smart City. In the latter case the concept of a smart city is formulated and builds up around optimizing implementation of following five key ideas [9, 10]:

- The win-win exchanging/sharing of goods and services between citizens and communities, using the common heritage or private property;
- The minimum environmental consumption and energy efficiency (minimal environmental/carbon footprint of the city), by recomposing the mix of energy consumption and the self-production of renewables;
- The free and fluid communication among social stakeholders (citizens, communities, companies, and institutions) using new digital technologies;
- City wide integration of new information and communication technologies, robotics and intelligent systems that maximize delivering needed information just in time;
- The network operation, which is the basis of resilience, to: 1) achieve maximum security of supply of goods and services with the right energy and environmental consumption; 2) make good use of the available infrastructure, and 3) provide the necessary social communication that will enable the city to adapt and recover functionalities in case of an impact.

Implementation of these ideas may include changes in the design and management of: 1) infrastructures, with emphasis on the redundancies and interconnections; 2) interdependent services, focusing on the ways they could support each other in case of an incident; 3) behavior of citizens in critical situations (the fundamental strategic element for improving urban resilience).

Ecosystem Resilience is the capacity of an ecosystem to *resist damage* and *quickly recover* after experiencing such stochastic disturbances as extremely high or low ambient temperatures, fires, flooding, wind and sand storms, tsunami, tornados, insect population explosions, and harmful human activities – deforestation, fracking for oil extraction, spraying of pesticides, and introduction of exotic plants or animal species, to name a few.

Disturbances of sufficient magnitude or duration can profoundly affect and may force an ecosystem to reach a tipping point (threshold) beyond which the system starts operating under entirely different set of regimes. Human activities that adversely affect ecosystem resilience (reduction of biodiversity, over usage of natural resources, pollution, and anthropogenic land-use and climate change) cause regime shifts in ecosystems, most often to less desirable and degraded conditions.

Interdisciplinary discourse on resilience now includes consideration of the interactions of humans and ecosystems via *socio-ecological* systems, and the need for shifting from the maximum sustainable yield paradigm to environmental resource management which aims to harmonize and build ecological and social resilience.

Climate resilience can be generally defined as the capacity of a socio-ecological system to: absorb and adapt stresses imposed upon it by climate change, reorganize and evolve into more desirable configurations that improve the sustainability of the system, leaving it better prepared for future climate change impacts. The key focus of climate resilience efforts is to address the vulnerability that communities, states, and countries currently have due to the environmental consequences of climate change. Currently, climate resilience efforts encompass social, economic, technological, and political strategies that are being implemented at all levels of society, with technological strategies being the core issue which attracts all other strategies as its satellites. From local community action *via cities* to global treaties, addressing climate resilience is becoming a priority. Although a significant amount of the theory has yet to be translated into practice, there is a robust and ever-growing movement, fueled by local (urban) and national bodies alike, towards building and improving climate resilience.

Urban resilience and sustainability. There are different system traits directly related to urban resilience: sustainability, vulnerability, flexibility and the like. As such, the concept of resilience is of great relevance for both urban city managers and politicians and they should be encouraged to manage cities through a resilience-based approach.

Urban resilience and vulnerability. Cities have always faced multiple risks over time. All cities that survived over the centuries and millennia of their existence have demonstrated their resilience in the face of resource shortages, natural hazards, and conflicts of various nature. The 21st century tectonic global shifts – climate change, disease pandemics, economic fluctuations, and terrorism – pose new challenges to the places we live. The *urban vulnerability* of a city is understood as *weakness against any harm* (like, exposure to floods, earthquakes, release of toxic chemicals and tsunami).

Dynamic urban resilience. Consequences of welfare impacts also depend on *micro-economic resilience,* which depends on the *distribution of losses*; on *household vulnerability,* such as pre-disaster income and ability to smooth shocks over time with savings, borrowing, and insurance; and on the *social protection system,* or the mechanisms for sharing risks across the population. The (economic) welfare disaster risk in a city can be reduced by: (1) decreasing exposure or vulnerability of people and assets (reducing asset losses); (2) increasing macroeconomic resilience (reducing aggregate consumption losses for a given level of asset losses), or (3) increasing microeconomic resilience (reducing welfare losses for a given level of aggregate consumption losses).

IV. Quantitative description of resilience

The above *verbal* description of the resilience concept lacks tools that would allow solving numerous problems related to assessing and controlling (managing) resilience as a quantity. Below such an apparatus is described. A generalized quantitative definition of resilience and preparedness is given by taking into account that most of the multiple parameters on which resilience/preparedness is dependent, are random variables (RV), random functions or random fields (RF).

Therefore, resilience is also a RV or a RF, and also is an explicit function of time. Hence, it is possible to quantitatively define resilience (as a rough first approximation) as follows [11]:

$$Rsl(t) = P\begin{pmatrix} N_t < N_*(0),\ E < E_*; \\ \Delta RDP \le \Delta RDP_*; \\ \Delta t_r < \Delta t_*,\ C \le C_*,\ 0 < \tau < t \end{pmatrix} \tag{1}$$

where $P(N_t < N_*(0))$ is the probability that the number of injuries/lethalities during the incident or catastrophe (and after, while mitigating its consequences) will not exceed a specific number during the time *t*; $P(E < E_*)$ is the probability that the volume/monetary value of the environmental damage during mitigating the catastrophe will not exceed a specific value during the time *t*; $P(\Delta RDP \le \Delta RDP_*)$ is the probability that the decrease of the regional domestic product will not be larger than a specific value during the time *t*; $P(\Delta t_r < \Delta t_*)$ is the probability that the acceptable recovery envelope time will not exceed a specific time; $P(C \le C_*)$ is the probability that the cost of recovery of the region will not exceed the forecasted value.

To this definition some quantitative measures should be added that refer the incident mitigation to the human factor (applied to the whole population involved in the crises): amount of suffering – total hours of being out of the comfort zone; number of mild, medium and serious illnesses; numbers of injuries, limb losses and lethalities (classified by age, gender, profession).

Now the strategic preparedness would be defined as a complex characteristic of a city, which resilience parameters [see formula (1)] are not less than some benchmark values. The latter could be obtained through solving corresponding optimization problems or real life statistics.

I. The architecture of the urban resilience system

The architecture of the urban resilience system (URS) mimics the long time existing on the market different monitoring and maintenance optimization systems designed to optimize performance of critical industrial infrastructures [2–4]. The difference is in that the urban infrastructure, in its entirety, is a very specific complex system of interdependent systems (SoIS) and is widely spread and some of its part *continuously moves* over the whole territory of a municipality. The URS is designed to provide, in the first place, raw and processed data about how this SoIS functions, and to some extent, but much less, about how it degrades in time [9, 10].

A typical URS consist of following elements (which can be purchased at affordable prices that have lowered more than 80 % in the last 10 years, and continue to drop): *sensors, geolocation subsystem*, *information subsystem*, *security subsystem*, and the *situation room SR*, which serves as the ultimate place where the decision makers *formulate, simulate* and *calibrate* their actions in response to different incidents, emergency situations, and catastrophes.

Sensors for an URS measure, in real-time, following parameters of the urban SoIS: traffic over different routes; occupation of public spaces; track public transport vehicles position in time; measure the levels of utilization of urban services (to optimize operations); health parameters (to protect the population); understand and track deficits and remaining works on the sheets. Sensors can be embedded into not moving and mobile objects, smart things, which also are a part of an overall URS architecture.

The *geolocation subsystem* consists of: GPS units attached to all moving components of the CI, information panels in public spaces; information (Data Bases) concentrated in social networks; capabilities to exchange information through transportation systems.

The *information subsystem* is comprised of: transversal overview in real time; simulation scenarios and decision outcomes; exchange of information between all the stakeholders. It is tethered to the *Internet of things* (IoT). The latter is a fast emerging industry and a wide meaning concept. Basically IoT refers to a remotely controlled «thing» connected to the Internet. In general, the word «*thing*» in an urban environment means *consumer things* [wearables, different home and garden appliances (heaters, air conditioners, water sprinklers, etc.)]. *Enterprise Internet of Things* (EIoT) connects things within the Business-to-Business environment (i.e., diagnostics, control, monitoring and maintenance system for a plant or a smart city district). A viable IoT solution contains *six distinct layers:* 1) *Devices* (heart of the IoT, the hardware able to gather the relevant to UR data); 2) *Enablers* (hardware that offers intelligence to *dumb* devices; 3) *Connectivity* (means that enable sending the data collected from the device to the server); 4) *Middleware/General Purpose Platforms* **(**transform the *machine language* into the *application language*, store the data, manage the devices (read data, send control commands to the device, authorize, authenticate, audit and account), as well as any alarms, events and notifications; 5) *Intelligent Services Suppliers* companies that offer services for the hosting applications (*Public Cloud*, *Private Cloud* or *Space* for your own server, take care of *Big Data Analysis*, creates patterns for predictive maintenance, data compression systems, etc.); 6) *System Integrator* companies have a key role in this industry as they design solutions, install and connect things, adapt software, unify systems, and interconnect software from different vendors (new and pre-existing software) In other words, they pull all the above together to make it work. *Telecom Operators* own the Internet connectivity, allowing to connect the things to the server where the application will be installed. The main parts of this URS architecture are shown in Fig. 1 [9].

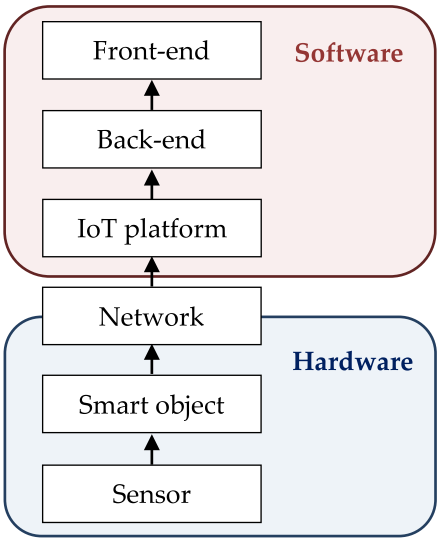

Figure 1: *The main components of the urban resilience subsystem*

V. Critical infrastructure models

The *software of the urban resilience subsystem* consists of a set of models that can be divided into three groups: 1) conceptual (verbal) models, which are results of corresponding identification processes combined with discretization procedures and accuracy assessments; they are used as input data for simulation; 2) calibrated models that are considered as a valid representation of the *natural system.* They have to account for the second type of uncertainty, which arises from the improper extension of calibrating conditions to prediction, i.e. not taking into account changes in the natural system or the scale of the problem); 3) mathematical (quantitative) analog, analytical, and numerical models. Approximate models are often used as decision support tools, as they are able to evaluate the relevant advantages and disadvantages of each alternative and rank the options. In practice, this is usually all that is needed for decision-making.

One of the most relevant problems in risk analysis of complex systems is the construction of adequate models of critical infrastructures (CIs). These models should lead to simple and effective quantitative methods of risk analysis and management of urban systems of CIs. Complex systems are characterized by that: 1) The interaction of its subsystems (elements) is hard to present explicitly; 2) The input data which describes functioning of the various elements of CIs is heterogeneous; 3) The traditional models, based on series-parallel connection of CI elements not always give an adequate description of CIs; 4) Implementation of the logic-probability models and graph theory models demands great efforts and presence of substantial prior information on the subject of research, which is not always available. Most effective in many cases are descriptions of CI as transportation, supply and Bayesian networks.

Consider an important and complex interdisciplinary integration problem – managing safety of a critical infrastructure (CI) of a large municipal area or a region, embedded into the context and realities of the modern society of risk. When analyzing risk it is necessary to answer three mutually dependent questions: Is the considered system of CIs safe enough? What is the size of risk? At what level of expenditures and efforts it is worthwhile to spend to save lives? There are two major approaches to this daunting task.

The first one could be characterized as the *from top to bottom – FTTB* or *from top-down* models. This approach largely ignores the small and medium scale events and zeroes in on state or regional scale consequences [e,g., the Leontieff Input-Output (I-O) model]. The second approach could be called the *from-bottom-up – FBU* models. It builds the risk model as a *quilt*, using as its *bricks* corresponding results of solutions of problems that relate to elements of critical infrastructures, and, finally, systems of CIs. It also is comprehensive, repeatable, rigorous, sophisticated, and based on real life statistics, permits true multidisciplinary block-module approach, when the output of the *i*-th problem is the input for the (*i*+1)-th problem. It also provides a natural way of assessing the domino-type disaster scenarios. This approach (*as related to industrial and natural disasters*) is institutionalized by a series of Federal laws and EMERCOM regulations and ruling documents. According to these rulings *every entity* that is considered a potentially dangerous object (PDO) is obliged to provide a *declaration* and a *passport of its safety*, and a *risk map*, which depicts the individual risk in the territory of the site and its surroundings. These documents contain: quantitative description of the operational risk of this entity; description of the needed mitigating means (machines, transportation, materials, workforce, and financial means) for the *worst case scenario* and the *average scenario*. The risk (failure) analysis is conducted using a set of state approved recommended practices (RP). These RP's are based on solutions of relevant problems of fracture mechanics, blast, fire, spill, filtration, water and air pollution, and descriptions of their consequences in typical scenario settings; provide some guidelines as to how to assess the number of fatalities and the monetary value of lost life or limb; prescribe how to assess the damage inflicted by a catastrophe and to present the collective risk specific for the PDO in consideration.

The *FBU* approach to command and control operations in emergency situations does not as yet fully address the problem of evaluation of the emergency resource management for regional resilience and strategic preparedness. Currently, there is no coherent, collaborative system in place to evaluate different risk scenarios, and to enhance communication to benefit from the unique and specific experience of each PDO as an organization.

VI. Selecting risk mitigating control (management) means

The last problem that crowns the full solution of urban risk management is designing and implementing risk mitigation control means. There are two approaches to solve this problem. The direct problem is posed as follows: With *given means* for improving CIs safety S_{giv} choose such a set of measures that *maximizes reduction* of incident probability $Q_i = P / A$. The inverse problem is formulated in following terms: With *minimal expenditures* EX choose such a set of measures, implementation of which lowers the incident probability $Q_i = P / A$ down to an *acceptable* (preassigned) level $P_{acc}(A)$. The above methodology was successfully implemented in creating risk maps for large municipalities and its satellites, power grids of several regions, pipeline systems, and other types of PDOs [12].

VII. Intrinsic specifics of critical infrastructures

CIs are large distributed renewable geotechnical man – machine – environment systems with: (1) non-economical responsibility (human factor, environment); (2) functional, structural and time-wise redundancy; (3) geometrical, physical, statistical and economical non-linearity.

Modern CIs have following indispensible components: risk-based diagnostic subsystems; monitoring and/or control subsystem(s), et al; risk-based integrity maintenance subsystems; assets safety and security/defense subsystems, and other. The total risk of operating CIs is carried by its full group of scenarios (100 %). All these specifics should be consistently accounted for during the design, operation and risk assessment of urban PDOs and CIs.

Urban ICI networks can be considered as *conduits* and at the same time as *intermediaries* between the natural environment and the resource demands of the urban society [13]. ICI is also the principal source of technological hazards of the city. A point failure anywhere in the ICI can rapidly propagate through the city with broad impacts on the citizens and the environment. Hence, it stands for reason that *management of urban risk may be boiled down to management of risk for the whole urban system of ICIs*.

The problem of urban resilience management consists of following two parts: Assessing the full possible damage and all of its components; Designing means and methods for reduction the potential consequences of an initial failure in the system of ICIs. This problem can be solved *only through interdisciplinary approach*, and by convoluting the heterogeneous parameters, which define the operation of the CI, into few integral parameters, which should be simple to understand and use.

The main conceptual problem of assessing, monitoring, and managing resilience/risk of ICIs is defined by following three factors: the dimension of the problem is huge (could be tens of thousands of interdependent parameters); the problem is multi-disciplinary, and the parameters involved when solving the problem are from different sciences and branches of engineering, and currently are, as a rule, hard, if not impossible to convolute; the ICI risk cannot be adequately described without explicitly accounting for the human factor. Hence, before attempting to solve the problem in consideration, it is necessary to introduce some *unified measures of safety/risk*, which account for the human factor in socially meaningful terms.

VIII. Proposed quantitative unified criteria for resilience/risk management

Authors proposes [14] following five generalized criteria: ICI Resilience; Regional Average Life Expectancy (RALE); Regional Life Quality Index (RLQI); ICI Carbon Footprint: ICI Entropy. Important comment: Public safety and security is an important objective, but diminishing of risk requires additional expenditures. The share of resources that is being devoted by society for achieving safety must be continuously evaluated, having in mind other needs of society, such as clean air and water, healthy food, housing, health care, social security benefits, pensions, education, etc., which also improve the longevity and quality of life.

Therefore, the central problem of regional (ICIs) risk management becomes optimization of the distribution of the always limited resources to improve the overall safety of systems of ICIs, and via this, the urban safety. This paper describes principles and methodology which lead to achieving this goal.

I. Probabilistic definition of urban resilience and strategic preparedness

It is best to first visualize the Resilience Factor, see Fig. 2, where *RDP* is the regional (urban) domestic product; *N*(*L*,*l*) is the number of casualties (*L*), injuries (*l*); (*E*+*A*) is the environmental and property losses; *U*(τ_0) is the vector of full losses. The corresponding problems are solved using appropriate probabilistic methods.

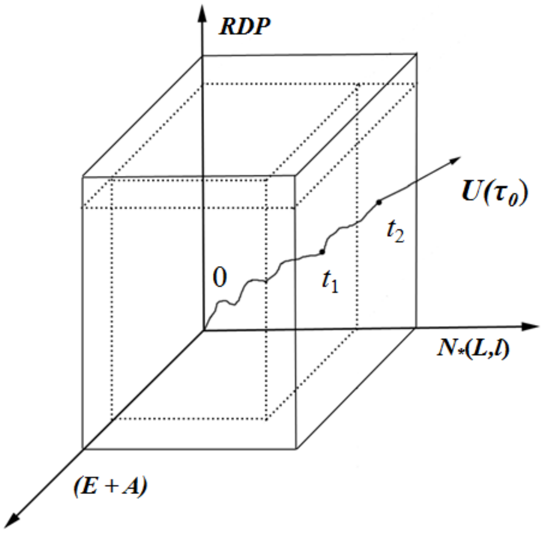

Figure 2: *Full and partial resilience factors*

Actually, Resilience Factor RF is an *n*-dimensional vector. In order to visualize each component of this vector it is recommended to deploy the vector, portraying each component of the RF vector as a two-dimensional function of time (Fig. 3). In this figure it can be seen that after the disaster the CI output *O* is decreased and it takes some time to restore *O* to predisaster values. The same pattern is observed for the RDP of the damaged CI. The losses *S* of limb and health of the citizens can be compensated, but it takes more time than in the previous case. Finally, the loss of life is permanent, as it will last forever. In reality, there are more components of the resilient factor RF.

Further analysis involves considering different scenarios of development of the restoration phase of the damaged CI, each of which has its own probability of developing (Fig. 4). Assessment of these probabilities is a very important, but separate part of the analysis and is derived via computer simulation.

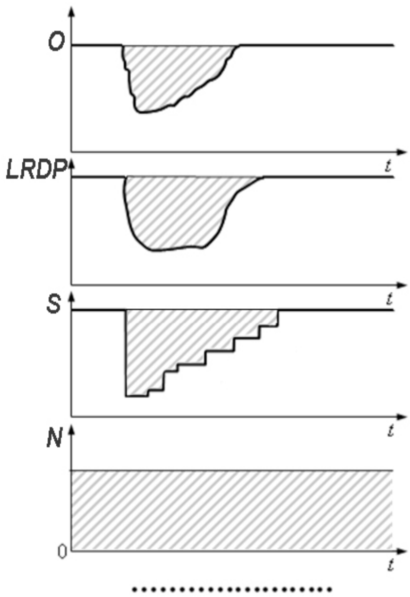

Figure 3: *n-dimensional collapse of infrastructure operating quality due to a disaster or a catastrophe: O – Output; LRDP – Lost growth RDP; N – non recoverable losses; S – recoverable losses; the dashed area relates to the n-dimensional volume/area of the quality collapse*

The FAQs when solving this problem are: What are the quantities of supplies required to meet the contingent demand of sheltered citizens? How far in advance must these supplies be ordered and pre-staged? What *level of uncertainty* in disaster forecasts exists at the critical decision points? What are the consequences of delaying such response decisions as related to supply? These questions have only probabilistic answers.

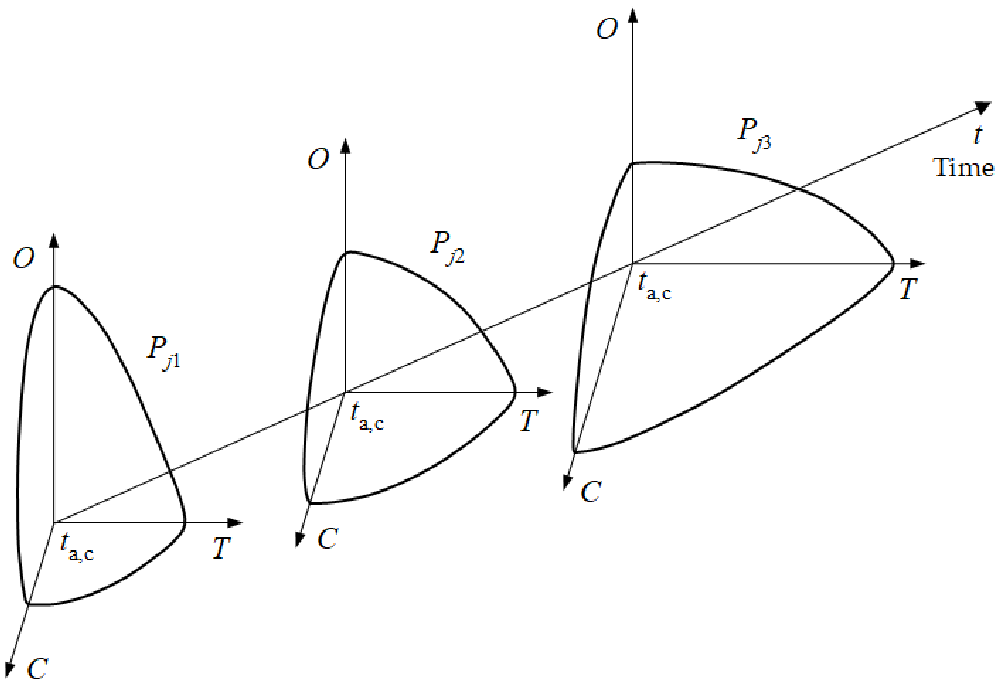

Figure 4: *The change of the partial infrastructure resilience* $Res_j(t)$ *in time for different probabilities of an incident/disaster/catastrophe and size of losses.*
$t_{a,c}$ *– time of the disaster; C – cost of recovery; T – duration of recovery; O – volume of lost production/services*

IX. Urban average life expectancy (UALE) as generalized criteria for optimizing city resilience

One may ask, why UALE? There are many reasons why UALE could be effectively used in urban risk analysis and management. The most valuable asset of any society is its people. The most valuable trait of a human being is her/his life. The most valuable parameter of a human life is its longevity in good health. UALE at birth is a non additive (non linear) parameter which permits combining parameters of complex safety of elements, structures and ICI systems with economic parameters of the operation and social aspects of sustainable development of the region. UALE provides seamless tying up of separate specific problems of safety/reliability of CIs and their elements with the generalized problem of regional risk management. UALE is a convenient characteristic for assessing the quality of life, because it continues to make sense with the size of the society in consideration shrinking. It is possible to calculate ALE for the nation/country as a whole, as well as for a separate region, industry, ICI, PDO and even for an individual. UALE has a biological «ceiling» (currently, just below 125 years) and some properties of a fractal, is a solution of a system of differential equations and has the form of a logistic curve which is a function of time. It depends on the current value of UALE and on how optimal the society distributes year by year the regional DP on accumulation of wealth, consumption, and on safety of the system of the ICIs, its employees, and the population adjacent to the same ICIs from the possible influence of incidents of different nature (Nature, technological, premeditated). In the last component it is necessary to single out those means (shares of UDP and of the PDOs budget), which could be (are) allotted to mitigate disasters and catastrophes of the ICIs' components and, accordingly, define, what would be the decrease/increase of the number of fatalities/injuries in the region in consideration due to natural/technogenic incidents, and assess how quantitatively this will influence the UALE.

The necessity of balancing the benefit from increasing safety (i.e., in the context of the problem in consideration, increasing UALE), and the cost of decreasing risk is an imperative of the XXI century and professional obligation of decision makers who are responsible for the safety of people. The ability of any society to prevent premature death/injury of its people is finite and restricted by its capability to create societal wealth. Hence, the *central problem of management of any risk (including technological risk) becomes optimization of the distribution (by volume and place of application) of the always limited resources to mitigate risk using the UALE criterion.*

X. The stakeholders of urban resilience

The stakeholders of urban resilience are four major different groups of organizations: 1) multilateral bodies (key to the urban resilience market, as they provide financing for UR improvement projects in emerging and developed cities, management and its benefits to citizens, economic operators, and decision-makers, support of policies for improving resilience; 2) research centers, which play a fundamental and vital role in this regard; 3) businesses that catalyze UR development; 4) governments of all caliber cities who are the end users of the UR product.

The hotspot in implementing the resilience concept in every day management of cities is in creating and using specially tailored software. Several such packages already exist and are being offered in the market [9, 15, 16]. For instance the HAZUR® software package [9] has been used to optimize management of several large and small cities in Catalonia (Spain). Besides improving public image, it helps creating an effective resilience subsystem of the city (installation of sensors for diagnostics and monitoring), for studying, analyzing and managing the city resilience, and *optimizing* the compatibility, coordination, operation of different services (agents) based on gathered data, allows to run simulations to illustrate how the city will react in the case of an impact

[17, 18].

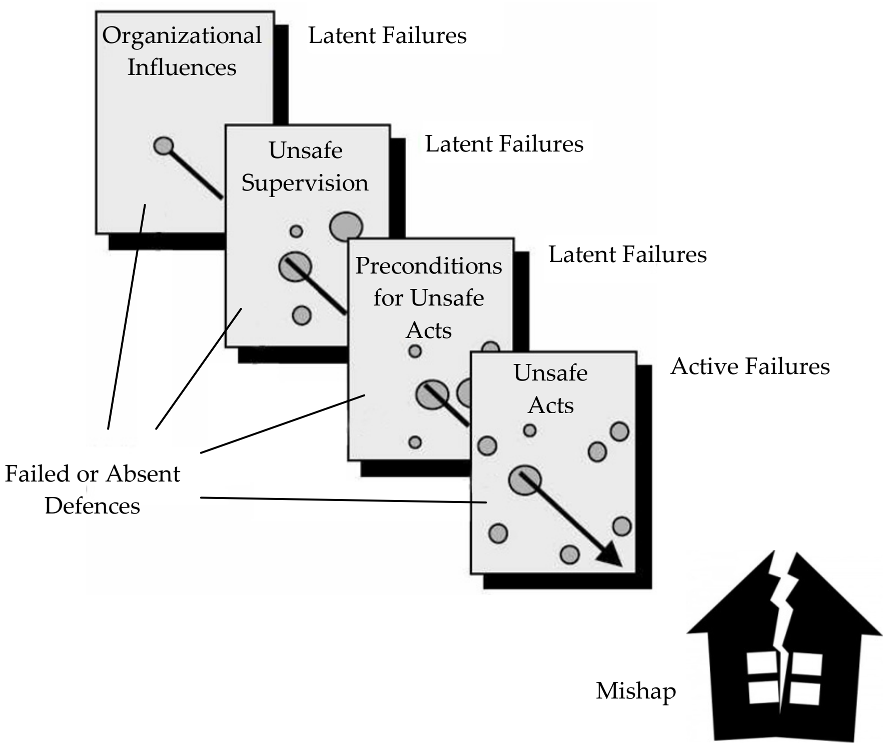

Figure 5: *The «Swiss Cheese» model of human error causation [19] adapted for the HFACS taxonomy by D. Wiegmann and S. Shappell [20]*

XI. Conclusion

1) Initial results of an interdisciplinary project on developing a methodology of urban risk management via risk governance of ICIs systems are presented.

2) The proposed methodology may serve as a useful tool for managing risk of PDOs, critical infrastructures and their systems according to the RALE criterion.

3) Results of the research may be useful to the municipal level decision makers (DMs), who make decisions related to optimal distribution of their budgets, taking into account sustainable growth of entities under their jurisdiction. They will also be able to monitor how their decisions influence the quality of life/level of happiness of their constituents as related to the decisions they make in the disaster and ordinary times.

4) In order to implement the resilience methodology to create a smart sustainable city it is necessary to build up for it an urban resilience subsystem URS, its architecture outlined in this paper, and create in its frame work a Resilience Office that is the core of dealing with urban crises and systemic stress. This URS would identify the weakest spots in the urban System of Systems and react faster and more efficiently during and after an impact or crisis.

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