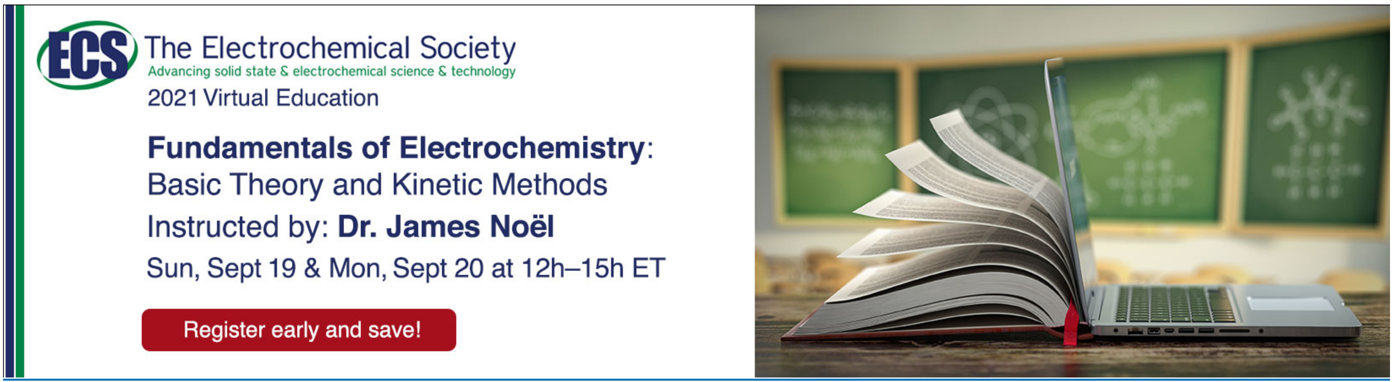
IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Black-Swan Type Catastrophes and Antifragility/Supra-resilience of Urban Socio-Technical Infrastructures

To cite this article: S A Timashev 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **972** 012001



IOP Conf. Series: Materials Science and Engineering **972** (2020) 012001 doi:10.1088/1757-899X/972/1/012001

Black-Swan Type Catastrophes and Antifragility/Supra-resilience of Urban Socio-Technical Infrastructures

S A Timashev[1,2,3]

[1]Science and Engineering Centre «Reliability and Safety of Large Systems and Machines», Ural Branch, Russian Academy of Sciences, 54-A, Studencheskaya, 620049, Yekaterinburg, Russia

[2]Ural Federal University, 620002, 19 Mira, Yekaterinburg, Russia

[3]Old Dominion University, Norfolk, VA USA

E-mail: TimashevS@gmail.com

Abstract. This paper may be one of the first attempts dealing with the problem of creating, providing and maintaining *antifragility* of systems of interdependent urban critical infrastructures (CI) in the wake of black-swan type technological, ecological, economic or social catastrophes occurring in a municipality. A synonym is offered to describe antifragility from a *positive psychology* perspective, formulating the problem as the *supraresilience* problem. A brief description is given of the developed innovative approach for creating a supraresilient city/region using black-swan catastrophe and the antifragility concepts. Resilience metrics are formulated as well as methods of assessing damage, interdependence of infrastructures and convergent technologies and sciences needed for practical regional resilience and risk management of the system of systems (SoS) of interdependent urban critical infrastructures).

1. Introduction

The *black swan* and *antifragility* concepts and their mostly phenomenological theories and empirics introduced to the broad public by Nassim Nicolas Taleb (N.N.T.) [1,2] are based on in-depth and convincing analysis of modern finances and macroeconomics, seamlessly coupled with the wisdom of a plethora of Ancient and modern philosophers and leavened by anecdotal and apocryphal cases, mostly from the Levant, Ancient Greece, Ancient Rome and other Near Mediterranean countries.

These concepts are based on three *whales*: (1) profound nonlinearity of *mysterious unknown* random processes of time and financial transactions that rule the financial world of NYSE, NASDAQ and the like; (2) extremely rare events that now and then shock World macroeconomics, create and bring super expensive chaos into lives of millions if not billions of people; (3) ability to see and use the intrinsic asymmetry of the optionality principle to one's (*non-sucker, in NNT's parlance)* benefit. However, their generalization onto other sectors of human activity, science and engineering (practically, to all walks of life, as energetically offered by N.N. Taleb in [2]), need some serious bricolage (adjusting, calibration, tinkering), for we all know: *the devil is in the details*. For potential users considered in this paper (urban decision makers DMs), without specific tinkering this approach may turn out to be counterproductive or an overkill.

2. The Black Swan catastrophe (BSC) concept

According to N.N. Taleb, the black swan catastrophe (BSC) is an event with following attributes: (1) it lies outside the realm of regular expectations (is a huge surprise not only to broad public, but also to the very specialists who designed the system in consideration; in our case, any urban critical infrastructure); (2) it results in (relatively) massive, catastrophic losses; (3) despite being an outlier, risk analysis specialists every time explain the next BSC occurrence *post factum*, making it look as an explainable and predictable event (although actually, it is *unpredictable*).Originally this kind of unpredictability was attributed by N. Taleb exclusively to macroeconomic and financial events. Later, this concept was applied with mixed results by other authors to some other sectors of technology and sciences [3,4].

It should be noted that the BSC as an event is scalable and is *intrinsically conditional.* One could imagine a BSC of global dimension (say, the unexpected and unpredictable Krakatau earthquake, Indonesia, 1897; global financial catastrophes of 1929 or 2008), as well as regional, local and down to personal scale BSC, when a stakeholder or pensioner loses her savings/assets in a surprise (for her) bankruptcy of a company. These conditions could be unknown to (1) the world scientific community; (2) a group of people who were affected by the BSC; (3) a single person due to lack of needed knowledge and/or false perception of the BSC before it happened.

Taleb further gives a classification of the super-rare events: he recognizes black-, grey- and white-swan (benibn rare) events, claiming that he deals only with black swans in macroeconomics and finance. In this context we will consider two types of BS events: in economics, which we will denote as BSE_e, and in Mother Nature or second, man-made Nature, which will be denoted as BSE_{ph}.

The grey-swan events in the field of economics were taken care of by the famous mathematician, Benoit Mandelbrot, when he introduced his fractal theory [5] and showed that many events (distribution of wealth, revenue from selling books of different authors, etc.) obey not the exponent-based Gaussian probability distribution function (PDF), but the more complex power PDFs with so-called *fat tails.* N.Taleb remarked [1] that due to B. Mandelbrot, who was first to use a more accurate and consistent in macroeconomics PDF (namely, the Pareto PDF, that possesses a fat [or heavy] tail), to describe BSE_e, the latter were transformed into *grey* swan events, as they started to be to some extent more predictable. Here it would be appropriate to recollect the famous adage: *The tail wags the dog.*

The white black-swan events are benign, because they produce (very rarely) great benefits, not losses.

Engineers and scientists from the oil and gas industry produced [4,6,7] their own classification of black- swan type events. They recognize following industrial BSE_{ph}: (1) completely unknown to the scientific/engineering community (*unknown unknowns* up to the moment of their occurrence); (2) unknown to the specific /local scientific/engineering community, but known if considered worldwide (unknown knowns – *unknown events to some (suckers), known to others (non-suckers)*); (3) *well known*, but considered extremely unlikely to happen during the entire lifetime or the timeframe between consecutive inspections or maintenance of the designed structure/system (say, a main pipeline or a sea-shelf platform). The tsunami that destroyed the Fukushima Daiichi nuclear power station is a typical example: in that region of Japan there were previously observed (in the 6-th and 13-th century) more severe tsunami, but the probability of them reoccurring was so minuscule (once in a *million* years), that it was deliberately ignored. If the unfortunate nuclear power plant had been built just several meters higher above ground, or had a levee built around it, the critical pumps wouldn't been flooded and there would be no Fukushima catastrophe, and no belated surprise that it happened.

Other BSCph are of the perfect-storm type (when all the components of such an event are well understood, but the probability of them emerging *simultaneously*, creating a *negative synergy* effect is so miniscule that it is deliberately ignored [8]), like the Guadalajara hail storm (in July 2019) when some parts of this city, according to the Washington Post, were covered by a *five feet high* layer of hail; or the 2019 flooding of New Orleans when a storm wave, wind-induced wave and the Mississippi flow created a synergistically combined wall of water that drowned the city.

There are attempts to make more reliable predictions of industrial and natural catastrophes using some combinations of brainstorming and computer modeling [9–13]. The forecasters now claim that some weak signals could serve as early heralds or precursors of BSE_{ph}, although the time to it will still be an unknown. Some clues from global warming, cosmic events or animal behavior can be effectively used for this matter.

In physics and engineering sciences statistical analysis of rare events is performed, using such PDFs, as Freshet, Gumbel, and Weibull, to name a few. Using the Bayes methodology these PDFs can be continuously updated after each occurrence of a rare event. This permits meaningful assessment of probabilities of stronger accidents and catastrophes in the above-mentioned fields

BS events that take place in modern physics, industry and all types of engineering (BSE_{ph}) do not have the devastating effect that is demonstrated by BS events in macroeconomics and finances (BSE_e). The reason for this is that the forces that play out during an industrial disaster are limited by location, physical laws, size of the installation, and the reached level of sophistication of the technology in containing energy, the only exclusion being nuclear energy and nuclear war. Natural catastrophes can be more violent than any human folly, but they also erupt locally, are contained by the size of planet's continents/oceans and laws of mechanics and physics. Damages from BSE_{ph} always have natural physical limits that could be reasonably assessed. Even in a potential Armageddon-type catastrophe involving the whole Universe we have a number, called *googol*, that cannot be exceeded. Bottom line: All engineering accidents are much less grey than Mandelbrot's grey-swan catastrophes.

Some BSE_e that happen in finances and macroeconomics, on the contrary, deliver a global blow to virtually every country, alongside with millions of stockholders. BSE_e are not contained by the actual combined cost of the world's physical and intellectual assets. The combined value of stocks (financial instruments) traded on all the major stock exchanges (in New York, London, Tokyo, Berlin, Shanghai, Moscow, etc.) is several times larger than the combined value of the physical assets that they represent. The BSE_e defy prediction explicitly because despite availability and accessibility of all the enormous amount of financial and economic data, generated every second, statistically it is not homogeneous. It consists of "real" data (reflects the physical assets, and "virtual" data (reflects the speculative component and human perception of what the stock may be priced in the future), without any means to parse it into real and virtual. That parsing the data into homogeneous sets is impossible is reflected in the famous mantra: «*All costs are already accounted for in the current price of stock*». There are, obviously, many other reasons for the financial market to be a classical black box, but their consideration is beyond the scope of this paper.

Modern economic and technical systems as they become more complex and interdependent are becoming more vulnerable in respect to accidents and catastrophes. The consequences of industrial catastrophes continuously grow with time due to the negative synergy of damaging effects (leak/rupture + fire + blast + destruction of assets + pollution of air/soil/water + loss of life-days, limbs and life + loss of revenue, trust, reputation and prestige). Many BSE_{ph} became transboundary, international. Industrial and natural catastrophes are becoming a serious destabilizing factor that prevents sustainable development of cities, regions and countries.

The rate of occurrence of industrial accidents is still high despite all the efforts to pull it down. According to [14] in 90% of automobile accidents the culprit is the driver(s); in aviation and river transportation up to 83% of catastrophes have human factor HF as the root cause; the same holds true in the energy field – 80% of industrial accidents are due to mistakes of the field personnel; in sea catastrophes 75% of them are related to human mistakes and mishaps; in railway transportation the corresponding number is 50%. According to [15], the HF in technogenic catastrophes frequently comes down to such human traits as stupidity, neglect or greed. All in all, it can be stated that the weakest link in the industrial safety problem is the human factor. Similar numbers apply to accidents in interdependent urban critical infrastructures. Hence, in order to drive down the probability of BSE_{ph} we should turn our attention to the role of HF in their occurrence.

What can be put against this tendency? Foremost, teaching safety culture to all employees of all ranks. And creating an atmosphere that stimulates active search of vulnerable points of the infrastructure being maintained. In this context, the popular motto in the 1980s of a giant American corporation: *To err is human. To forgive is not company policy*, spread worldwide (author came across it while lecturing at Milan Politec) as a cartoon in which a designer standing in front of a drawing board is beaten with a stick from behind, today would not be well received by employees or by the broad public. Instead of punishing, a tolerant climate is needed, where everybody freely communicates, and upper echelon of listens to the lower. Forming safety culture is the universal tool for not allowing wrong actions of personnel that lead to mishaps and accidents.

Industrial catastrophes are developing in a continuously deteriorating man-made environment. The health of deteriorating structures and machines is periodically or continuously diagnosed and monitored, providing operators and owners of the assets with robust data using which sound assessment of their residual life can be obtained. This permits controlling the operated system in time, using risk based predictive maintenance methods.

3. The fragility-antifragility concept

N.N. Taleb justly and correctly describes the fragility-antifragility concept as a specific *current* property of any object, tacitly indicating that antifragility is an explicit function of time. Fragility is a well-known property in structural mechanics, that defines low ability of an object to resist external and/or internal harmful factors. In English language there exists a near-synonym of this word: *brittleness*, that has a more negative connotation than fragility (e.g., *brittle* diabetic, but a mentally *fragile* old relative). Its antonym is *ductility* or *viscosity*. Some strong viscous metals like steel alloys and structures made from them become brittle when exposed to very low temperatures (below minus 50 degrees Celsius). This phenomenon brings to life the urgent design problem of creating cold-climate-resistant pipelines, transportation and ground moving machinery for the Far North, Arctic and Antarctica regions.

In Russian language the word resilience – *живучесть* – refers both to live and dead (non-animated) objects and means that a system is able not only to rebound after being released from a stressor, but also continue to exist (stay alive/operate) when being injured/damaged and perform its functions under stressor or duress as designed by humans or God. According to the Ozhegov Russian dictionary *живучесть* describes the ability of a system (say, a battleship), to stay afloat and continue to fire, using its *remaining* internal strengths, while having its scull damaged by adversary's artillery. In this context the word *непотопляемый* (unsinkable) is also used in relation to boats and humans alike. A perfect visualization of this notion can be seen in a Russian doll called *ванька-встанька* which means *the stand-up vanya,* or *неваляшка* which can be translated as *roly-poly* (Fig. 1). Being forced into a horizontal position and then released, it immediately pops up back into vertical position. Hence the name of the doll.

Figure 1. The roly-poly doll that perfectly illustrates the classical resilience concept.

Antifragility, on the contrary, did not exist as a notion before Nicholas Taleb introduced it in 2012 as an antonym to fragility and demonstrates itself as the ability of a system to become *stronger* (up to an unknown point) *after* experiencing a stressor. If the stressor exceeds this unknown level (which itself is a random function of time), the person instead of accruing antifragility may become seriously harmed and loses his initial capabilities. Hence, antifragility is principally more than resilience or robustness. Taleb uses this connotation (antifragility) only in relation to live or complex objects – human beings and the Mother Nature (biological and ecological systems). He also admits that complex systems can be antifragile, obviously meaning, by default, that their complexity must include the human dimension. Antifragility is a trait that *exclusively* exists in *living* objects, because mind-/spirit-less (*dead*) objects have no ability to proactively react to different stressors of economic, financial or emotional, as well as of physical nature so as to become *more resilient/strong* than *before* the stressors were applied. Creative human action is essentially needed to achieve that part of antifragility that is *beyond* resilience of non-animated objects as we know it.

All objects created by human beings cannot become stronger after being treated by a vector of physical or chemical stressors (loads and/or influences),as they are intrinsically fragile, but this statement may soon not be fully true. There is already one case related to a nano-tube carbon composite material that became *stronger after* being physically stressed [16]. An ever-growing amount of research is conducted addressing self-healing and resilience of critical infrastructures, specifically power and information networks. In the literature that emerged after 2012, the antifragility idea as a trendy topic started to be misused, being mechanistically applied to such inert (dead) man-made systems as architectural design and buildings [3]. In the latter case authors seem to confuse *moral longevity* of buildings and cities (their capability to absorb technical innovations – growing automobile and streetcar traffic, elevators, influx of population, etc. *without change* or becoming extinct) – with antifragility. If I buy a pair of Levi's jeans a couple sizes larger than my current waist and then wear them until I feel them tight on me, I cannot claim that these jeans all the time were *antifragile*. In order to be antifragile they must adjust by *themselves*, *without human intervention*, to the size of my waist and self-repair, if need be.

Antifragility comes from and is revealed by mostly yet unknown inner forces of every human or biological being (i.e., bear, turtle, sequoia tree, etc.) or their population (i.e., rats, bees, ants or human communities) as reaction to different types of stressors. These forces are triggered by thirst for life, freedom, pursuit of happiness, all kinds of extreme challenges, lust for power, sex, wealth, fear, hunger, ultimate anger/fury, obsessive love, vanity, extreme circumstances (e.g., low/high ambient temperature or pressure), words of encouragement, patriotism, faith and sense of duty, drugs, and so on. In general, *it is a manifestation of biological vitality which is, by itself, the force of life*. Probably, because of this, *antifragility* was always nameless and word-(expression)less, understood by *default* by humans for millenniums as an intrinsic indelible component of vitality and, hence, never (before Taleb) became a separate issue for a philosophical discourse.

It is not fully known what happens in the body, mind and spirit of an individual when she/he is exposed to some specific stressor/ set of stressors. The outcome (positive or negative) of such event may come down to *overreaction/overshooting*. This phenomenon is responsible for preparing a biological system to become more powerful in the future in relation to the applied specific stressor (load, poison, cold/hot ambient temperature, etc.), when the stressor will be stronger than the experienced last time. It may be not a universal type of response of the system to stressors. In some of the cases, hidden abilities of humans are revealed immediately, in the face of extreme danger, as in a documented case when an Arctic pilot, wearing heavy arctic gear and being attacked by a polar bear, saved his life jumping directly from the snow onto the plane's wing (approximately two meters from the snow surface) and getting into his cabin [17]. Schizophrenics during their bouts of wild insanity accrue the ability to lift weights (throw heavy oak tables on nurses or lift the back of a taxi car to prevent it from moving away), impossible to lift for them when in normal condition. A champion (of the Warsaw Zoo) chimpanzee (average weight—60 kg), that does not have human conscience and does not fully understand the environment and capabilities of his own body jerks from chest a 650 kg bell bar (nearly 11 times his own weight); on average, a Warsaw Zoo chimpanzee jerks 450 kg [17]. Currently the men's world record in this heavy weight discipline (category up to 56 kg) is only 198 kg (3.54 times the record holder's weight). (This huge difference can be partially explained by that chimpanzee's arm muscles are wired differently from human arms muscles, although they are also longer than ours. It seems that this is the price humans pay for having consciousness). Rats, when being decimated by humans, using poison, traps and other lethal means, demonstrate an unusual antifragility as a cohort. They start intensive breeding, and new-born rats reach puberty at the tender age of two weeks, still being blind [17].

It should be noted that if the stressor is exceeding some ultimate level, the person exposed to such a stressor produces such an overshooting that makes him not stronger, but weaker/sicker, and she/he falls into the subset of fragile components of the system, becoming not a system's asset but its burden/liability. The type of PDF that governs the antifragility skills is a mystery (known unknown), but one could speculate that physical antifragility is closer to the Gaussian distribution rather than to the Pareto type distribution: genius is always a very rare commodity. The distribution of cognitive antifragility skills, though, probably could be better described by the Pareto type PDFs. In any case, when creating a smart city, some empirical data on antifragility has to be used as a guidance for selecting the city resilience team.

With the advent of global digitization, AI and robotization, some forecasters predict that by 2060 AI will match human intelligence [18]. The current level of computer science and AI already permits adding some elements of (quasi-) antifragility to *cloud computing* [19] and creating *emotional* robots, that are able, at least partially, to have a semblance of human emotions (quasi-emotions) and, hence, to some extent understand human psyche. It seems that with the advent of time some 21-st century robotic systems may be able to *maintain and repair themselves* to continue to operate «as new» or «as before the stressor was applied» (this is resilience in its classical meaning [20]), and if need be, to reconstruct themselves to become more smart and durable (for instance, during an unmanned expedition on the Moon or Mars), by adding to themselves new modules with new functionalities and higher resistance to unforeseen stressors. This would be an act of what could be called *resilience plus, ultra-resilience, uber resilience* or, best, *supraresilience (*in Taleb's parlance, *antifragility),* realized by a man-made system *without* direct human intervention.

According to Collins English Dictionary the word *supra* comes from Latin and when used as a prefix, means *above, over, on top of, greater than, beyond the limits of, outside of*. Obviously, it perfectly matches the word resilience to describe the result of overshooting/ overcompensating. Hence, *supraresilienc*e is a positive thinking absolute synonym of *antifragility;* therefore, both terms are interchangeable and from now on will be used as such. In addition, the term *supraresilience,* in general seems to be more fit for the physical and especially, engineering world, where the term *resilience* is very well established and currently is a hot topic of research.

In order to achieve the described above feat, the *supraresilient* robot must be equipped with a smart control subsystem that includes diagnostics, monitoring, maintenance, repair modules and a module that is able to upgrade the capability of the robot (a *self-upgrading* module). This subsystem, driven by IT and an AI «brain» brings the needed (quasi-) human dimension into the AI robot to achieve the needed supraresilience/antifragility, as it can, using a two- or three level maintenance/control policy [21], mitigate the damage due to a black/gray swan event and raise the robot performance to a level higher than that of the initial design.

In many branches of modern industry (military, nuclear power, automotive, oil and gas, aviation and the like) there are already unmanned robotized and flexible production lines equipped with these types of modules. They have in place subsystems that autonomously and automatically carry out diagnostics, monitoring and, to some extent, maintenance. For instance, according to data that can be found in the Internet, the performance of the entire fleet of F35 airplanes is tracked by a software system that provides holistic life support of each detail and aggregate of every airplane of the fleet.

The same source forms that the European Airbus company is in the process of equipping all airplanes of its fleet with an array of sensors on every aggregate, overhead baggage bin and each passenger chair that generate in real time gigabytes of data related to the airplane performance and the feedback of its passengers and flight attendants. This Big Data is streamed to the cloud and the on-ground servers and immediately analyzed, using the Airbus digital analytical platform *Skywise*, which will also be fed by data from repair shops, spare parts suppliers, airports and airlines.

Using *Skywise*, by 2023 each Airbus plane will have its own *digital twin*. While the carbon/titanium airplane will fly, its quasi-identical digital twin will do the same, but in virtual space. The discrepancies between the current state of the real airplane and the state of its digital ideal copy will be analyzed for detecting early predictors of possible future malfunctions or accidents. This platform opens new perspectives in flight safety, flight traffic control and optimization. This philosophy is also used by Airbus to create a passenger multicopter (flying taxi) for the city mobility project Vahana.

One doesn't need to be a prophet to predict that all the above achievements will be sooner than later emulated and adopted by modern smart cities of all sizes.

According to N. Taleb, antifragility is implemented by using its main tools: *choice* and *option*. Freedom of choice permits choosing something that leads to more benefits than losses, while option = asymmetry (specific non-linearity) + rationality, could be a substitute of knowledge (in everyday life). N. Taleb doesn't describe how to diagnose, measure, and control the antifragility property in humans during their lifetime. It is obvious though that in a community or society antifragility is spread according to some Weibull type PDF that is a function of time. It also should be specific to each type of antifragility (physical, cognitive social). Each person, no matter of what antifragility level, must learn how to recognize the options and the asymmetries around her/him and at the workplace and how to make sound decisions in the chaotic environment of the 21st century, keeping in mind that there are *no free lunches*. In the areas of physical and engineering environment though, specialists have many tools to describe in quantitative terms the options and the asymmetries as well as the tools that help making right and sound decisions. At this point we stop further considering this topic as it is beyond the scope of this paper.

4. Resilience of urban critical infrastructures: current concept

Some 10–15 years ago city managers around the world realized that industrial diagnostics, monitoring and maintaining systems could be relatively easily adapted and used to optimally run and maintain all city production, transportation and life support facilities. At the beginning, they were slow in implementing these ideas but now, with the advent of digitization and AI, have accelerated their efforts to transform their cities – large and small – into smart cities.

In the above context the concept of resilience emerged currently as a central theme of industrial and urban development (there are more than 120 definitions of resilience, most of them are qualitative) Sustainable cities of the 21-st century must first be safe, resilient, and, consequently, smart in order to then become sustainable. For cities to be safe and smart they have to be resilient in the first place [22]. In general, factors that influence city resilience include: the range and severity of hazards; the risk to life, limb, health and property; the vulnerability and exposure of human, social, and environmental systems to different types of hazards, and the degree of (strategic) preparedness of the physical, social and the governance systems to any natural, urban or industrial shocks and stressors and their consequences during an incident, accident, malicious act, or catastrophe.

The architecture of the urban resilience system (URS) [23] mimics the long time existing different monitoring and maintenance optimization systems designed to enhance performance of critical *industrial* infrastructures. The difference is in that the *urban* infrastructure, in its entirety, is a very specific *complex system of interdependent systems* (SoIS), being widely spread over the whole territory of a municipality, being 1) intensely used by the city community and 2) elements of its transportation infrastructures (cars, trams, buses, metro carriages) continuously move. The URS is designed to provide, in the first place, raw and processed data about how this SoIS functions and degrades in time.

System resilience consists of following components: 1) *Structural resilience* (reliability, probability of failure); 2) *Structural safety* (risk level, damage zones, all types of losses); 3) *Physical restoration subsystem* for renewing a damaged system. This subsystem can vary by means of recovery (e.g., democratic or authoritarian), time and cost of restoration, amount of materiel, financial and human resources necessary for restoration; 4) *Psychological restoration subsystem* for the stressed-out society. This subsystem also varies by the amount of psychological assistance and the duration of its provision, as well as by the required human, materiel and financial resources.

Structural resilience is the ability of a system to maintain its functionality after being stressed by loads greater than their design values or after a specific damage. Critical infrastructure has many functions; therefore, CI has both complex (integral) and partial resiliencies. Both full and partial resiliencies are always conditional. Since the properties of CI and the stressors that it experiences are random, the resilience is also random and can be measured as the probability that the CI will retain its function(s) under any specific random effect that is *beyond the design parameters*. The term *robustness* is strongly related to the term *resilience*, as it means that the system is stable – it gives a weak response to a strong disturbance.

The *strategic readiness* of a CI is such a state of the system when it remains reliable, relatively safe and efficient to perform its main design functions, even with *sudden application of extraordinary, way out-of-design* values of external influences. This can be achieved only by including into the CI a deeply echeloned protection subsystem. A case of a one-dimensional stochastic model of failure and recovery of infrastructure as a system is shown in Fig. 2.

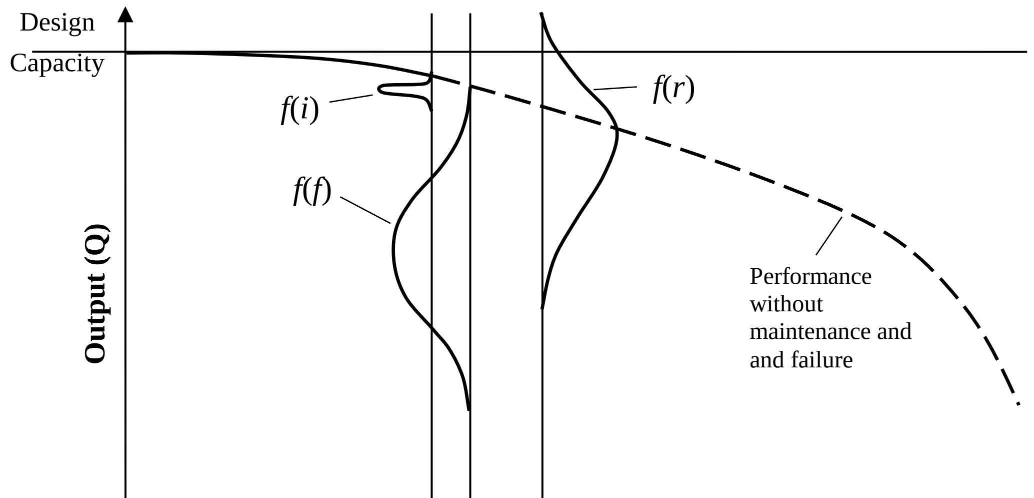


Figure 2. One-dimensional stochastic model of failure and recovery of infrastructure as a system: t_i – time to incident; t_f – time to system failure; t_r – time to recovery; $f(i)$ – PDF of the initial triggering event duration; $f(d)$ – PDF of damage volume due to system failure; $f(r)$ – PDF of recovery quality.

According to the Rockefeller Foundation: «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.»

Resilient systems refer to those institutions, cities or states that have the ability to reconstruct and to recover, using the right tools, assets and human social and cognitive skills to deal with impacts and *resist, absorb* and *adapt*. The challenge here 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 European Commission defines urban 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*».

The author's 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, health, elements of Mother Nature (flora & fauna) and assets; i.e., components of the second, man-made Nature], but also to the quantified ability to quickly recover to the *pre-event physical* and *psychological* state after a disaster or catastrophe at as minimal as possible cost.

To assess the conditional regional resilience (and strategic preparedness) in relation to a hypothetical catastrophe or accident that occurred within the ICI system under consideration, it is first necessary to *identify* the region whose infrastructure has been damaged. For instance, to estimate the regional resilience in the case of an impact/stressor (hurricane, deliberate actions of intruders, etc.) on a large municipality (which includes industrial and civil buildings and structures that produce commercial products and life support services for the population living in it), following initial data is needed:

- GIS with a database (DB) on the topography, population density (number, gender, age, profession), locations of damaged critical assets and installations, roads, waterways, etc., and how they are interconnected, including information about their owners;
- Type of threats / stressors under consideration (earthquake, flood, technological disaster, resulting in deaths, loss of limb, injuries, pollution of air, water bodies, landscapes, etc.);
- A stochastic description of the considered regional threat (impact);
- The design of the infrastructure in question, including types and number of various structures, buildings and installations that make up the infrastructure and the type of their interdependence (physical, informational) that determine the robustness and innate resilience of each structure and the infrastructure as a whole;
- Statistical characteristics of the physical components of these ICI;
- The volume and form of available resources for mitigating and eliminating the consequences of the disaster (finances, labor, materiel, transport, road-building machines, food, etc.) of the region itself and additionally attracted from outside;
- The socio-demographic description of the society living in the territory occupied by the ICI.

Having the listed above initial data, it is necessary to:

- give a description of the primary failure of a system element that initiated the catastrophe per se;
- define the areas affected by the incident (destruction zones) and assess the social risk and materiel and human losses from the accident, with accounting for the possible cascade development of the catastrophe;
- define the vulnerability / fragility curves (VC/FC) of each CI that got into destruction zone. These FC establish the dependence of the conditional probability of a specified damage of a structure on the magnitude of the received impact. Generalized FC are obtained by integrating specific FC over the entire areas of possible external influences, and the physical properties of the structures and infrastructures' materials. FC, in combination with the results of the analysis of the volume and nature of real damage to structures from one or another type of impact (i.e., earthquakes, hurricanes, technological explosions, etc.) allow (via appropriate calibration) accurate enough assessment of the number of damaged structures and the level of destruction of each individual asset. These problems are solved using statistical dynamics methods.
- Determine the likelihood that the described above region, subjected to a stressor, will recover (from the damage level determined at the previous stage) to the level «as it was before the accident» within the given directive period of time, using a specific amount of allocated

recovery funds. This stage problems are solved using the statistical operations research methodology.

- Evaluate the time and volume of necessary material and non-material means for bringing the society back to the previous, pre-emergency level of the psychological state of security and well-being, knowing the volume and composition of the destruction of critical infrastructures and human losses.

To solve the above problems following tools are used:

- The «bottom-up» model of regional economic recovery [22,23];
- A full group of events, including all conceivable scenarios with the cascading development of a natural or man-made disaster (involving people whose cognition skills include rich imagination to construct such scenarios);
- A rational (quasi-optimal) plan for responding to an accident and rebuilding a damaged facility, based on considering an as full as possible set of scenarios, including accidents with minimal and maximum consequences.

The above approach allows minimizing the consequences of an accident by optimizing: the distribution of food and water among victims of a disaster; the sequence of repair of electrical networks, gas, water, sewage, etc.; localization, retention and collection of oil spills; road cleaning; maintenance of shelters; distribution of sandbags for the construction of dams, etc. Direct and inverse problems of restoring damaged critical infrastructures of the region also become solvable. *The direct task* gives an assessment of the funds needed to restore the regional infrastructure given the amount of damage and the preset recovery time; *the inverse problem* determines the necessary time for the restoration of regional infrastructure with known volumes of losses and the allocated financial and material resources (see [22,23]). These problems are solved iteratively using the Gantt and similar type networks.

All the above allows for the effective management of regional ICI and of the society related to these ICI, at normal times and times of various crises. Decision makers (DMs) at the level of municipalities and territories receive an instrument of support and substantiation of their decisions. It is no secret that due to lack of time and the lack of flexible tools, many decisions are often taken on a hunch, especially when it is necessary to consider the long-term consequences of decisions. Using the above approach, DMs will be able to track how taken decisions affect the quality of life and the level of satisfaction of their wards / voters.

A typical development cycle of a single accident of a complex infrastructure in time consists of three stages: (1) normal functioning and systematic preparation during its maintenance for the prevention of potential disasters $\left(0 \le t \le t_0\right)$; (2) failure of any component that initiates damage to the infrastructure and the development (most often, cascade) of a system accident $\left(t_0 \le t \le t_1\right)$, and (3) its recovery to the pre-emergency state or better than (manifestation of *supraresilience* /*anti-fragility*) $\left(t_1 \le t \le t_e\right)$.

Each of the stages reflects, respectively, the ability of the system: (1) to resist the force impact (manifestation of the congenital structural resilience), (2) to absorb the initial damage (by controlling the stressed and deformed state of the system by: duplicating some of its functions, redundancy of multi-component systems, changing the design scheme, dampers, vibration dampers, arrestors of crack growth, etc.), and (3) recovering to the states «as before the accident», «as new», or «much better than new», depending on the plan for using the system in the future and the degree of anti-fragility of the creative DMs who own and / or manage the infrastructure in question. Thus, the system resilience is determined by its ability: (1) to resist mechanical forces, kinematic and degradation effects (the local failure initiating accident is characterized by an insignificant level of damage to the system); (2) to absorb the impact of the initial damage and minimize the cascading/chain failure length and its consequences. This quality is called robustness; and (3) to recover (quickly and efficiently regenerate all its design functional properties).

Strictly speaking, the ability to recover *should not be considered* an attribute of the infrastructure per se (although it is accepted in practically all publications on systems resilience), since restoration of the damaged or destroyed infrastructure is carried out by *another* (construction) infrastructure, while a *third* (financial) infrastructure serves as a source of funds for restoration. The ability to recover should be obviously attributed to the construction and financial branches of an enterprise that is the owner of the damaged infrastructure, or mainly to the construction entity that performed the task of recovery, if it was outsourced. It is also a function of the asset management ingenuity and quality, and of regional governance specifics. Hence, system resilience Res_{Σ} consists of two parts. One of them (Res_{str}) is the resilience of the physical system per se, the other, Res_{rec}, is the resilience of *another* infrastructure, namely the one that conducts or governs the recovery of the damaged system:

$$\mathrm{Res}_{\Sigma} = \mathrm{Res}_{str} + \mathrm{Res}_{rec}. \tag{1}$$

Likewise, the psychological supra-resilience also does not belong to the damaged system, because this restoration is conducted by a fourth, medical infrastructure, although in many cases it is embedded as a matryoshka (nested doll) in the system being recovered.

5. Supra-resilience of urban critical infrastructures

As an intrinsic property of any socio-technological system that explicitly includes human society which consists of humans that are capable to adapt and make decisions based on to some extent free choice as its integral part, supraresilience can serve as the basis and tool for solving the most urgent issues of modern civilization. In order to describe *antifragility* from a mathematical point of view as a logical extension of something that we already know how to describe (this is the most often used mathematical technique in such cases) we can write that antifragility, conditioned on stressor Q

$$\text{Antifragility(Q)} = \text{Resilience(Q)} + \text{Overcompensation(Q)}, \tag{2}$$

or, fully equivalent

$$\text{Supraresilience(Q)} = \text{Resilience(Q)} + \text{Overshooting(Q)}, \tag{3}$$

Where overcompensation (overshooting) is the ability of the system to *improve its initial quality parameters* (whatever they may be) after being exposed to specific stressors Q (on the condition that they do not exceed some usually unknown ultimate limits. If they do, it injures/breaks the system).

It is also possible to define antifragility and supraresilience as only overcompensation / overshooting.

If we agree on this definition, then the definition of *urban supra-resilience antifragility* using the above European Commission description of resilience formulates as

Urban supraresilience (antifragility) is «the ability of an urban/regional system of systems of critical infrastructures to withstand, adapt, quickly recover from stresses and shocks such as drought, violence, conflict, natural, technological or man-made disaster, and at the same time improve/increase its initial vitality parameters.

It is interesting to note that in China, the only country on the world stage that survived for more than 5000 years without interruption, since ancient times exists a famous adage, which is used as a *curse*, not as a benign wish to one's antagonist: 愿你生活在变革的时代 (Yuàn nǐ shēnghuó zài biàngé de shídài). The English translation sounds as: *May you live in the times of change*. It seems that the Chinese society never cared much about the hidden antifragility of change and aimed at Confucius style *Ordnung*.

The antifragility phenomenon is unique for each person, and for that matter, community, or society, as it largely depends on one's genes or a pool of genes. Moreover, it is a random function/field of the person's age, level of physical and mental health, and the type, level and duration of the stressor imposed on her/him. Hence, for each type of stressor each person reacts by one's own antifragility feedback (overshoot). In order to effectively utilize one's antifragility it is necessary to know her/his boundary between the benign and the unhealthy levels of the stressor at any given time, which is a daunting, impossible task. There are no recipes for estimating these boundaries. Mankind does not know how to reconcile human ambitions and human possibilities, and there are no methods other than *debilitating* to test the strength of people. This statement seems to be true when testing the physical and mental abilities and the creative power of people, the latter being even more difficult, as it also depends on the level of one’s education and cultural upbringing. This leaves us with pure empirics when trying to assess the combined (integral) antifragility of an urban society working as a team to create an supraresilient smart city while operating, using and maintaining a system of systems of critical interdependent infrastructures.

The supraresilience is achieved only if there is some extra resource or a genuinely new design for the damaged system that permits *overshooting*, thereby creating a system more resilient than before the event. This is a manifest of the HF *supra-resilience* (creative persons) involved in the project. In general, everything of the man-made Nature that survived time could be considered as antifragility of the past generations accumulated and preserved in built structures and passed on to present and future generations.

6. The source of urban supraresilience

N. Taleb recommends [2] using the antifragility bell bar method when trading stock and conducting other types of stock exchange business, that makes the person smart.This is *advice that should be followed* by all urban DMs when they make macro economic decisions involving stock exchange. In cases related to engineering practices the regional DMs should follow recommended practices from multiple engineering sciences and convergent technologies as related to the areas of their expertise, activity and responsibility. For instance, using structural reliability and resilience methods, they should: (1) Simulate different scenarios of catastrophes. Each scenario produces its own results (loss of production, decrease of RDP, number of injuries, fatalities etc.) of the catastrophe and the resources and time needed to bring the system back to the state «as new», or «as before the catastrophe»; (2) Optimize predictive maintenance using the two-or three-level policy method created for optimizing mechanical systems [21].

The ultimate difference between the problems solved by the considered methods is in that in the sphere of engineering the losses due to a catastrophe never will be as large as in the stock exchange practice. Engineering practice has a sophisticated system of checks and balances in the form of safety design codes and regulations developed over the last 50+ years. The stock exchange business, for obvious reasons, still lacks such tools or methods of their effective implementation.

In order to fully understand the concept of urban antifragility demonstrated as supraresilience, it is necessary to consider the urban system of systems (SoS) of physical critical interdependent infrastructures that includes the human community as a separate social infrastructure in itself, that runs and uses the production/services of the SoS, and, simultaneously, *lives* in the space of these infrastructures (the *urbs* and the *civitas* [3]). When solving this problem, one must consider the interconnection of the Mother-Nature with the second, man-made Nature in an urban environment, looking through an supra-resilient lens that is in the hands of the smart community that runs the show in a city.

In the context of the main theme of the paper (BSC and antifragility) and taking into account its limited size, the remaining space of the paper is spent to describing in highly condensed form following aspects of urban/regional supraresilience: (1) resilience metrics; (2) methods for assessing the volume of damage caused by a specific set of stresses; (3) analysis of interdependence of critical infrastructures; (4) convergent technologies/science needed for conducting research on regional resilience.

7. Resilience metrics

To quantify resilience it is necessary to introduce some transparent, meaningful and simple metrics, easy to calculate and use for all of its components. These metrics can be given in absolute and relative values.

In structural mechanics and reliability design there are just a few quantitative metrics for resilience. Most of them were developed for using in design and are simply ratios of some crucial informative parameters of the design vs same parameters of a reference baseline. They are hard to use, because some of the parameters have to be known at a very early stage of design, before there is any possibility to assess them.

In [22] *structural resilience* was described as *reliability* of a performing structure when loaded by stressors beyond their design values. At the very moment the load on the system exceeds its design value, the structural resilience of the system is equal to its structural reliability and the reliability curve seamlessly transforms into resilience curve. Actually, resilience is described as reliability of a structure, when it is exposed to stresses caused by loads that are above their design values.

Resilience analysis proposed in [23,24] for systems allows assessing physical and relative consequences of the collapse of the quality of functioning of the ICI due to an accident or catastrophe It should be scaled on at least such parameters as: (1) decrease of the volume of goods and services produced by ICI, (2) losses of real regional domestic product RDP, (3) number of lost life-days, injuries, limbs and fatalities (irreversible losses). It demonstrates changes in partial resiliencies and the extent of damage of the infrastructure over time for different probabilities of an incident / accident / catastrophe.

The specificity of calculus of the partial resiliencies is in that while reliability, structural resilience and safety belong to one class of problems, the physical restoration resilience is an *entirely new problem*, which belongs mainly to governance, operation research and logistics. The latter problem is characterized by the time to recovery and its cost. The author proposes using as a resilience parameter for the recovery phase the ratio of the products

$$(\$recTrec) / (\$conTcon), \qquad (4)$$

where ($recTrec) is the product of the actual amount of money and time spent on the recovery of the damaged system; ($conTcon) is the same, for the same object, but during its construction.

The connection of these two groups of usually independent problems is in that solutions of the first group of problems provide the input to the second group of problems, which is a perfect example of how the infranetics' methodology works (more on this below).

In this paper, following [23,24], resilience is conveniently represented as a dimensionless random variable or function of time, as the ratio of the current resilience to the resilience embedded in the system during its design and realized during its construction and commissioning. Such a dimensionless relative resilience function (variable), by definition, cannot be greater than unity.

When repeating the accident-recovery cycle, the base resilience may already be different from that in the first cycle. Note that for each type of impact or combination thereof, it is necessary to perform a separate assessment of the system resilience with respect to the specific stressor. Only if the system receives (from its supra-resilience/antifragility component) the supraresilience property during its renovation/repair/recovery can it exceed unity. It can turn out to be an emergent property of the system only if the human factor (HF) is explicitly introduced into its composition, namely, those DMs who decide which recovery strategy to choose, to what level of productivity / efficiency and by what (calendar) time to bring back the damaged infrastructure, based on the regional needs and specifics of its governance.

The calculation of resilience as a regenerative ability of a system requires stochastic modeling of emergency response and the process of restoring damaged infrastructure. Here, the baseline is resilience, calculated using «standard» rules and techniques, allowing to put the system into operation at the pre-set time.

All the above reasoning was carried out regarding the generalized productivity of the system. Exactly the same reasoning can be carried out for other types of partial resilience, such as: throughput, volume and speed of providing various services, percentage of population covered by a specific service, number of critical facilities available for use (e.g., housing, grocery stores, medical, educational, cultural, etc. institutions), providing opportunities for private and individual economic activity, etc. A set of partial resiliencies that covers all vital aspects of life of a regional society is considered as full.

For calibrating the algorithm that models the object recovery process, statistics on past accidents and recoveries should be used, whenever and wherever possible. This results in more accurate partial resilience curves of real damaged objects.

8. Methods for assessing the volume of damage caused to an infrastructure by a specific set of stressors

A quantitative assessment of system resilience due to its ability to adapt consists in assessing the degree and nature of the destruction of the whole system by a fixed value of overload. This is done by constructing the so-called fragility/sensibility curves FCs [25], which link the magnitude of the impact on the system with the magnitude of its consequential damage in a probabilistic sense the generalized probabilistic risk assessment (GPRA) methodology can be effectively used for the evaluation of critical infrastructure performance risk. This approach started in the late 1970s as related to nuclear power plants and earthquakes, and are now used worldwide in order to assess safety of different existing or projected civil structures and power plants subjected to strong ground motions. It should be emphasized that there are no limitations to use this approach for other type of stressors and other types of infrastructures having in mind the possibility of a black swan event.

Fragility curves express the conditional probability of failure (CPoF) of a specific infrastructure or its component for a given specific stressor size (wind, wave, snow load, earthquake motion, etc). The bearing capacity of the structure is presumed to be known, via gathering statistical data or conducting computer simulation. Currently it usually is modeled by a Log-Normal distribution [18], but it could be also modeled by a Weibull PDF.

The key components of a GPRA study are (1) stressor hazard analysis, (1) fragility evaluation for each component and substructure and, (1) system analysis and construction of logical fault tree model. In their entirety, these three elements allow for the proper risk quantification of the installation (evaluation of the PoF due to the full set of possible accident scenarios). A hazard analysis yields a family of curves, each corresponding to a confidence level and thus accounting for uncertainty in the estimation of the specific hazard. This PoF can be expressed by convoluting the hazard curve with the fragility curve. The PoF conditioned on stressor level parameter *b* is given by the cumulative distribution function (CDF) of capacity *B*, yielding:

$$P_{f|b}(b) = \int_0^s \frac{1}{x\beta\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\log(x/B_m)^2}{\beta^2}\right)} dx = \Phi\left(\frac{\ln(b/B_m)}{\beta}\right) \tag{5}$$

where $\Phi(\cdot)$ is the standard Gaussian CDF. Hence, the FC is entirely defined by median capacity B_m and logarithmic standard deviation β.

The upgraded version of this formula accounts for two types of uncertainties by incorporating two random variables ε_U and ε_R with median equal to one and respective log-standard deviations β_U and β_R (β_U characterizes uncertainty in the knowledge of the median value whereas β_R refers to inherent (epistemic) randomness about the median). In this context, random bearing capacity is expressed as [25]:

$$B = (B_m \varepsilon_U)\varepsilon_R, \tag{6}$$

and the CPoF as:

$$P'_{f|b}(b) = \Phi\left(\frac{\log(b/B_m) + \beta_u \Phi^{-1}(Q)}{\beta_R}\right), \tag{7}$$

where Q = the level of confidence that the CPoF $P'_{f|b} < P_{f|b}$. Equation (6) defines a family of curves, each corresponding to a confidence level Q.

Considering the safety of an infrastructure composed of substructures and equipments (e.g., a petrochemical or power plant), the PoF of the entire system is determined by means of fault trees using simple logical structures of AND and OR in order to combine different events likely to result in global failure.

9. Analysis of interdependence of critical infrastructures

Interdependency is the main hot-spot issue when considering performance of urban critical infrastructures. Currently, there are following possible practical approaches to quantify this interdependence: 1) Analysis of the interaction of CIs in the form of transport networks (see Fig. 3); 2) Study of the interaction and interdependence of CIs using multiple regression theory; 3) Computer simulation of interdependence involving stakeholders (including building a *digital twin/ close relative* of the objects under study) based on the HAZUR-БИЖУР software [26].

The analytical models fit for this kind of research should allow finding in a comparatively simple way and without big errors numerical values of all types of damage and how they change in time. One of the most versatile models here would be the advanced transportation network model [27].

This practical synthetic model describes functioning of interdependent systems of critical infrastructures (ISCI), each of which is represented in the form of a transportation/services network comprised of nodes and directed links. Nodes typically represent physical infrastructure components (the so-called assets, such as electrical power producing plants, oil, gas and water processing units and installations, hospitals, industrial and office buildings, research and education centers, living quarters and the like), which are directly involved in supplying the population and local industries with different products or commodities, and services. The links of the network are modelling the flow (product transportation) between the nodes and may present electrical power grids, main and distribution gas and oil pipelines; water supply and sewage systems, as well as railways and highways, etc. The model considers the conditions and specifics of supply, delivery, overhaul, and demand of resources, such as electricity, hot and cold water, and removal of the industrial and human activity waste [27].

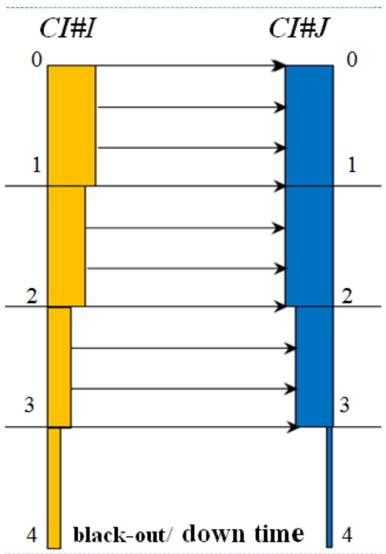


Figure 3. Visualization of interdependence of two CIs.

The specificity of solving such problems is in finding the critical points or thresholds when there appear changes in the normal (design) performance of interacting CIs (see Fig. 3). State (0–1) represents normal operation/performance of both CIs. State (1–2) is a state when the performance of both CIs is still normal, but the reserve of CI #/I capacity is severely depleted. State (2–3) means that any remaining reserve of the CI# I is gone and, hence, the consumption of CI #J is compromised. State (3–4) represents the case when the energy output of CI#I is zero, or close to zero, and the operation of the whole CI# I is brought down. The generic equation that describes the above situations has the form:

$$\sum \mathrm{E}_i(\tau) - \sum Q_i(\tau) \geq \Delta, \quad \left[\Delta = 0,\ \Delta_1, \Delta_2, \ldots \Delta_N;\ i = 1,2,\ldots M,\ 0 \leq \tau \leq T\right] \tag{8}$$

where $\sum \mathrm{E}_i$ is the energy output of the CI #I, $\sum Q_i$ is the energy consumption of the CI# I output, N is the number of performance change triggers, M is the number of nodes in the CI#I network, T is the total duration of joint performance of considered ICIs.

The second approach (multiple regression) is theoretically attractive but very hard to implement, since it needs a lot of reliable data gathered from real life cases. This data can be provided by the third approach, but once it is realized, there is no need for the second approach per se; it could be used for visualizing the results obtained by simulation. The main problem of implementing the third approach is in how to quantify the interdependence of the multitude of critical infrastructures that perform in or out of sync.

10. Designing the regional risk management /governance strategy using infranetics concepts

In order to create an optimal strategy of regional risk management a special tool is needed that would allow using multi- and inter disciplinary approach and various methods from different fundamental, applied and engineering sciences under one umbrella [29]. For this matter in this paper the new convergent science- Infranetics- based on the MAICS-convergent technology (Digital Stochastic **M**echanics, **A**rtificial Intelligence, **I**nformation Theory, **C**ognitive and **S**ocial Sciences) is used. The name Infranetics comes from I*nfra*structures+Cyber*netics.* Infranetics was constructed for solving the central problem of safe innovative development of a region/territory/municipality by creating a methodology of harmonized regulation of regional risk, based on optimal management of systems of interdependent critical infrastructures (ICI). A full description of the method can be found in [28,29]. In Fig. 4 the flow chart of constructing such strategy using the infranetics philosophy and tools is presented.

It can be seen that creation of such strategy involves a heterogeneous set of initial data and knowledge from multiple fundamental, applied, and engineering sciences. When solving this problem for some regions of the Russian Federation, the author came across several surprise info-gaps (most of them known unknowns) in macro-economics [30], demography [31], reliability theory of large systems [32], to name a few, which needed immediate attention, as they were roadblocks preventing reaching the assigned goal. It seems that in this case infranetics concept threw new insight into the research problem; advanced research in several fundamental and applied disciplines; greatly enhanced and expedited the research.

Accumulating results of this kind of interdisciplinary research permits understanding what methods from what disciplines belong to infranetics. The results, obtained by the above scheme, made it possible to effectively manage the SICI in different types of municipalities and territories (see [33–37]).

Infranetics manifests itself as a cross-pollinating complex-sciences discipline. It permits accurate-enough prognosis of the behavior of complex socio-technological and economic systems being designed or already performing, in usual and/or catastrophic situations. Infranetics uses goal-oriented approach according which a unified concept is formed that describes ways and means for solving the problem in consideration. If properly developed, infranetics could become the crucial convergent technology and discipline for governing smart supraresilient municipalities and regions in the 21st century [38].

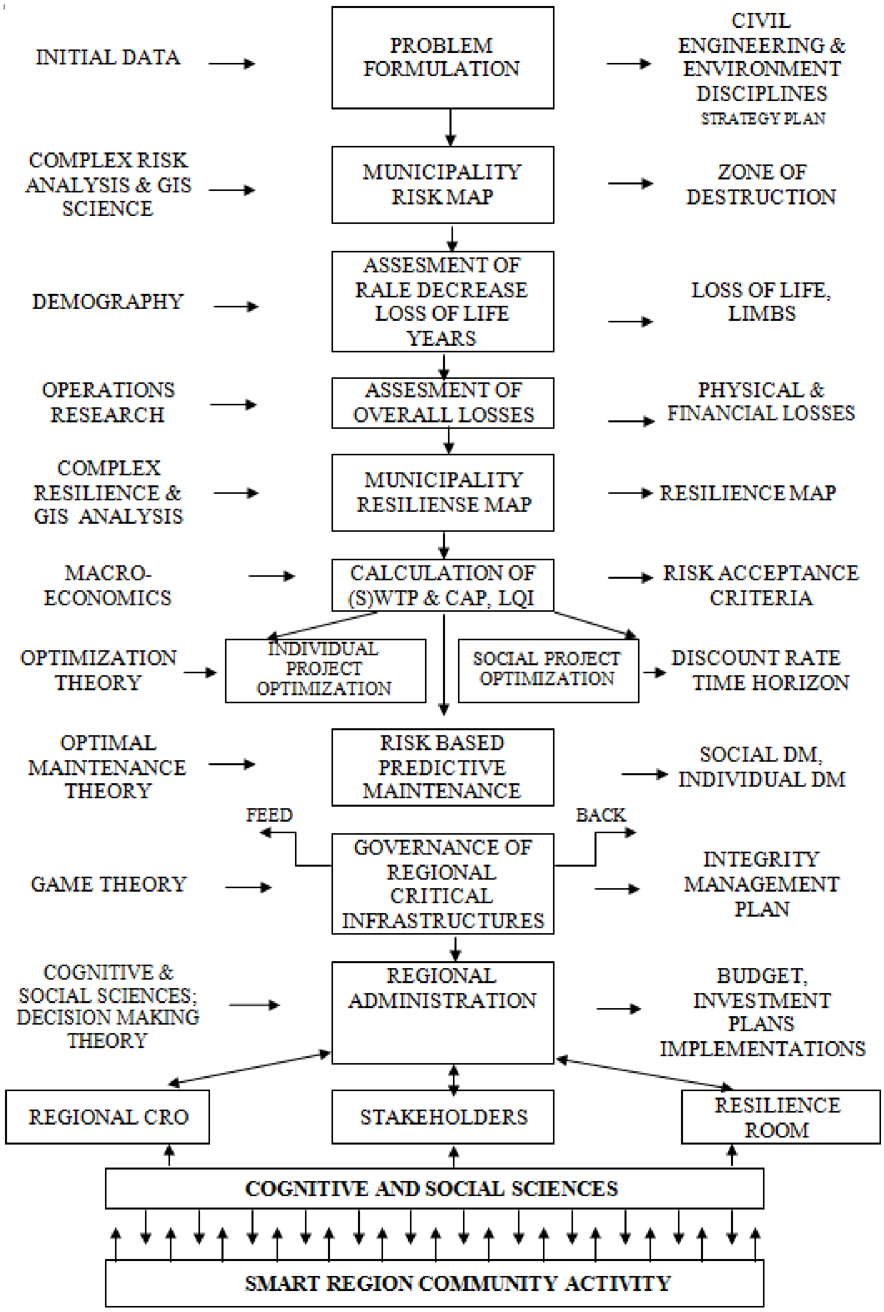


Figure 4. Regional governance strategy via regional resilience and risk management using infranetics principles and tools.

11. Conclusion

The resilience property is the ability of an infrastructure system to continue to perform its design functions in conditions when it is partially damaged and/or deprived of supplies, and with employees and population psychologically stressed. This circumstance is the unconditional and the sole basis for creating a reliable and safe smart territory. The concepts of acceptable risks developed for managing the technological, industrial and natural risks are quite compatible with BSE_{ph}.

Without resilience, it is *impossible* to create a smart region/city capable of sustainable development. Resilience is also necessary for achieving the long-term goals of strategic development of any region, which include developing human capital, improving the quality of life and increasing the competitiveness of the economy through the systematic introduction of services and innovative solutions.

Supra-resilience/antifragility should be a property of every socio-technical system, but it is not a given. All physical infrastructures are fragile, by definition. But if coupled with a supra-resilient component (i.e., high quality human factor) the socio-technical system can obtain needed antifragility traits.

For a socio-technical systems to be antifragile, its supra-resilient components should take care of all the system's fragile components. The supraresilient components in their term have to care of each other, using for that all methods that mankind developed to this day, including the «*skin in the game*» concept [38]. A structure can be designed to last (i.e., possess physical and moral longevity), be adaptable and accommodate new functions through intelligent design, construction, optimal maintenance and effective governance by the cognitive and creative components of the region/city that can face the unpredictable events.

The concept of supraresilience opens the door to meaningful exploration of quantitative dependencies/correlations between physical resilience of a system of systems of ICIs and the psychological/societal resilience of people who live inside and extensively use this system of ICIs in the context of different types of communities – from megacities, to big, medium size and small towns, to villages/settlements and tribal areas.

The effectiveness of the interaction of ICIs cannot be adequately described without direct consideration of the human factor (HF). Which profile specialists are best to pull off and solve this task? This question is open for discussion, but it seems that civil and environmental engineers, structural mechanics specialists and designers are best fit to take lead when tackling this problem.

References

[1] Taleb NN 2007 The black swan: the impact of the highly improbable (London: Penguin)
[2] Taleb NN 2012 Anti-fragile (London: Penguin)
[3] Ivan Blečić and Arnaldo Cecchini 2017 On the antifragility of cities and of their buildings *City Territory and Architecture* 4:3
[4] Aven T 2013 On the meaning of the black swan concept in a risk context *Safe Sci* **57** pp 44–51
[5] Mandelbrot B B 1997 Fractal and Scaling in Finance: Discontinuity, Concentration, Risk (Springer-Verlag)
[6] Aven T 2013 On how to deal with deep uncertainties in a risk assessment and management context *Risk Anal* **33**(**12**) 2082–91
[7] Aven T 2014 On the meaning of the special-cause variation concept used in the quality discourse-and its link to unforeseen and surprising events in risk management *ReliabEng Syst Safe* **126** pp 81–6
[8] Paté-Cornell ME 2012 On black swans and perfect storms: risk analysis and management when statistics are not enough *Risk Anal* **32**(**11**):1823–33
[9] Aven T and Krohn BS 2014 A new perspective on how to understand, assess and manage risk and the unforeseen *ReliabEng Syst Safe* **121** pp 1–10
[10] Hopkins A 2014 Issues in safety science *Safe Sci* **67** pp 6–14
[11] Masys AJ 2012 Black swans to grey swans: revealing the uncertainty *Disaster Prev Manage* 21(3):320–35
[12] Financial Post Deepwater rig worker weeps as he admits he overlooked warning of blast that set off America's worst environmental disaster 2013 http:// business.financialpost.com/2013/03/14/halliburton-worker-weeps-as-he-ad mits-he-overlooked-warning-of-blast-that-set-off-americas-biggest-oil-spil l-in-gulf/?__lsa=42e0-28bb [accessed 15.01.14]

[13] Kaplan S, Visnepolschi S, Zlotin B, Zusman A 1999 New tools for failure and risk analysis: anticipatory failure determination (AFD) and the theory of scenario structuring *Southfield* (MI: Ideation Inter Inc)
[14] Aronov J and Papic L 2018 Reliability and Safety Management of Engineering Systems Through the Prism of Black Swan Theory *In: System Reliability Management, Solutions and Technologies* (Boca Raton: CRC Press, Taylor and Francis Group) pp 103–112
[15] Lee Davis 2002 Man-Made Catastrophes: From the Burning of Rome to the Lockerbie Crash p 402
[16] Carey B, Patra P K et al 2011 Observation of dynamic strain hardening in polymer nanocomposites *ACS Nano* **5**(4): 2715–22
[17] Shwarts S 1969 Public Lecture of the Director (Institute of the Ecology of Plants and Animals, Ural Science Center USSR Academy of Sciences)
[18] Kurzweil Ray 2015 Evolution of the Mind (Moscow: Э)
[19] Brinnolofson Eric and Andrew McAfee 2017 Second era of machines (Moscow: ACT)
[20] Rene Gustavsson and Bjorn Stahl 2009 Self-Healing and Resilient Critical Infrastructures *In: Critical Information Infrastructure Security*
[21] Timashev S A 1982 Reliability of Large Mechanical Systems (Moscow: Nauka)
[22] Timashev S A 2011 Resilience and Strategic Preparedness of Critical Infrastructures *Proc. of the First Int. Conf. on Vulnerability and Risk Analysis and Management ICVRAM and the Fifth Inter. Symp. on Uncertainty Modeling and Analysis ISUMA* pp 764–771
[23] Timashev S A 2016 Infrastructure Resilience: Definition, Calculation, Application *WEEF, IGIP/ICL Conf.* (Pisa Italy)
[24] Timashev S A and Bushinskaya AV 2018 Structural resilience *Proc. Safety and monitoring of technogenic and natural systems: VI All-Russian Conf.* (Krasnoyarsk) pp 36–43
[25] Zentner I, Nadjarian A, Humbert N, Viallet E 2008 Numerical calculation of fragility curves for probabilistic seismic risk assessment *Proc. of the 14th World Conf. on Earthquake Engineering* (China Beijing)
[26] Timashev S A, Alekhin V N, Poluyan LV, Fontanals I, Gheorghe A 2018 Transforming Yekaterinburg into a Safe, Resilient-Smart and Sustainable City *IOP Conf. Series: Earth and Environmental Science* **177(**1) 012001
[27] Timashev S A and Bushinskaya A V 2019 Analysis of Interdependence of Arctic Critical Infrastructures as Transportation Networks *IOP Conference Series: Materials Science and Engineering* **481(**1) 012008
[28] Timashev S A 2018 Infranetics: The New Convergent Science for Risk Based Management of Systems of Interdependent Critical Infrastructures *Proc. of 27th Annual Conf. of the Society for Risk Analysis Europe: Risk & Uncertainty – From Critical Thinking to Practical Impac*t (Östersund Sweden)
[29] Gheorghe A and Masera M 2010 Infranomics *Int. J. of Critical Infrastructures* **6**(4):421–427
[30] Timashev S A, Tyrsin A N, Kozlova O A, Makarova M N, Voronina L N 2014 Methodical Approaches to Assessing the Influence of Budget Expenditures on Average Life Expectancy *Scientific Review* 7–1
[31] Bushinskaya A V and Timashev S A 2019 The Toll of Incidents, Accidents and Disasters on the Average Life Expectancy in Good Health *Proc. of the 29th European Safety and Reliability Conf* doi: 10.3850/978-981-11-2724-3_ 0614-cd
[32] Burukhina O, Bushinskaya A, Maltceva I, Timashev S 2018 Mechanical system reliability analysis using reliability matrix method *IOP Conference Series: Materials Science and Engineering* **365** 042067
[33] Timashev S A 2016 *Infrastructures. Part 1. Reliability and Longevity* (Yekaterinburg: Ural Branch of Russ. Ac. of Sci)
[34] Timashev S A, Bushinskaya AV, Malyukova MG, Poluyan LV 2016 Reliability and Integrity of Pipeline Systems (Yekaterinburg: Ural Branch of Russ.Ac. of Sci)

[35] Timashev S A 2013 Unified quantitative criteria for managing regional risk *Proc. of the 11th Inter. Conf. on Structural Safety & Reliability ICOSSAR* (NY: Columbia University)
[36] Guryev E S, Poluyan L V and Timashev S A 2014 Construction of dynamic risk maps for large metropolitan areas *J. of Risk Analysis and Crisis Response* **4**(2) pp 72–76 (Paris, France: Atlantis Press)
[37] Timashev S A 2014 Average life expectancy as a criterion for regional risk management *J. of Risk Analysis and Crisis Response* **4(**1) pp 10–19 (Paris, France: Atlantis Press)
[38] Taleb NN 2018 Skin in the game (London: Penguin)