Mechonomics: design thinking for growth and resilience of sociotechnical organizations

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Mechonomics: design thinking for growth and resilience of sociotechnical organizations

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Abstract
In this paper the principal ideas of mechonomics are introduced. Mechonomics is a neologism indicating the possibility of predicting the behaviour of sociotechnical organizations in the complex and interconnected world of the 21st century by means of models borrowed from structural mechanics. In particular, the concepts of growth, resilience and robustness of the organizations are discussed. The analogy with structural and natural systems is shown to be sound and permits to interpret the effects of the size of the organization and of its internal arrangement and collapse of enterprises and institutions. Consequence-based design, as the tool able to tackle with unpredictable stimuli and external effects, is introduced as the only robust philosophy that should pervade design and management of sociotechnical organizations.

Keywords: Mechanics, economy, resilience, societies

1. Introduction
In recent years, many authors have pointed out the need to take into account unexpected events during the functioning lifetime of a sociotechnical system (like, e.g., healthcare, education, transportation etc.). They borrowed from mechanics' terms like resilience and fragility to define the system's different responses to those actions. The different proposed approaches, however, still fail to provide models for designing and managing these systems in a quantitative and effective way.
In the literature, many attempts to transfer physical concepts to the realm of economics are reported. However, we have noticed that practical and applicable tools are missing. The term *econophysics*, as a subfield of statistical mechanics, includes methods developed by physicists to solve problems in finance and markets, usually including stochastic processes and nonlinear dynamics [1]. Georgescu-Roegen [2] applied the concepts of energy and entropy in economics, stating that the 2nd law of thermodynamics governs the economic processes. Despite the great efforts carried, e.g., to apply chaos and fractal theory to economics and finance, the results are still restricted to a qualitative reasoning.
The objective of the paper is to introduce new theoretical concepts and quantitative models and strategies to predict and control functioning, growth and collapse of sociotechnical systems like enterprises and institutions, starting from the rules of mechanics enriched by the theory of complexity and by the strategies of Nature. We believe that quantitative theories inspired by structural mechanics, adapted to the sociotechnical realm, can describe - with high degree of accuracy and in most circumstances - functioning, growth and collapse of sociotechnical systems.
Artificial and natural structures obey the laws of mechanics and show peculiar features at collapse. Mass and energy, resulting in forces and displacements, are the governing entities both at the micro- and at the macro-level. Mechanical quantities like stiffness, strength and ductility define the structural behaviour as elastic or plastic, robust or brittle. This is not a mere qualitative analogy, but we believe that the similitude between mechanical systems and sociotechnical organizations can be made quantitative if the concepts of "mass" and "energy" are properly identified - as analogies - in sociotechnical organizations like enterprises, institutions and groups of people. A pioneering and inspiring source of such analogy is the masterpiece "*Crowds and Power*" by Canetti [3], where the interplay between the masses and the power at the sociological level is investigated by means of metaphors.

Based on these assumptions, our target is to find innovative tools to control organization processes and predict their outcomes in a range of situations where established methods fail. The resulting theory may be called *mechonomics,* indicating tools and models borrowed from (structural) mechanics and applied to economics and social sciences. Deterministic and probabilistic models, defining the robustness of artificial and natural structural systems under loads and environmental stimuli will be adapted to sociotechnical organizations. Not only financial firms, banks and companies could benefit of the new tools and models, but also public institutions like large communities, health care and social security organizations could take advantage from the research results to control their processes and gain resilience and efficiency.
Dealing, e.g., with sociotechnical practices and organizations, already many years ago interaction design provided interesting observations about the co-existence of actions, activities and services. Later system design focused on the largest wholes that human beings create, examining in particular collective interactions (see, e.g., the concept of *fourth order design* by Buchanan [4]). Therefore, management theory naturally shifts into *design thinking*, as the four functional aspects of management (i.e., planning, organizing, directing and controlling) naturally belong to its realm. The 20th and the 21st century brought the failure of traditional management theories when applied to complex socio-technical systems like welfare, healthcare, environmental control, education, transportation etc. Some design thinkers argue that most of the disasters in these cases were caused by a lack of good human-factors and human-centred design [5].
We believe that complex sociotechnical systems are often poorly designed with regard not only to the lack of human-centered design but also to a lack of a wider *nature-centred* design. The result is that people in charge of these organizations are blamed for their errors although the problem is intimately rooted in the organization itself.
In this paper we will discuss crucial aspects of human-made organizations and show how simple lessons from the world of engineering (where basic physical and mechanical rules define all the performances), enriched with nature-inspired strategies and complexity, can provide resilience and robustness to sociotechnical systems.
The theories of *behavioural economics*, i.e., the study of the effects of social, psychological and emotional factors on the economic decisions of individuals and institutions [6], may seem in disagreement with our conjecture, as one may claim that the “human factor” is not present in mechanical systems. However, as evidenced by the game theory applied to economics, this is not true as what really counts at large scales is the *collective behaviour* of the population. We believe that sociotechnical organizations follow laws similar to those of complex structural systems made of a large numbers of elements. *Mechonomics* represents a new tool for a resilient and robust approach to system and service design, including human organizations, societies and cultures. Therefore, it can be considered as a tool in the context of design thinking, taking its origin from physics and mechanics and evolving into economics and social sciences [7][8].

2. The glossary of mechonomics

The words used in *mechonomics* take inspiration from the mechanics of materials and structures. That is, a small glossary is required before entering into the details. An every-day experiment can be used to describe elasticity and plasticity (Figure 1-A). Take an object (like a rubber band) in your hands and observe it: it has a shape (in the case of the rubber band, memorize its length). Now, it is time to apply forces to the object: pull, squash and twist it. When such “actions” finish, if the object is not broken, you can note either that the shape (or the length) is the same as at the beginning of the experiment, or that the shape is different, i.e., maintains permanent deformation. In the first case we refer to an *elastic* material, in the second case, respectively, to a *plastic* material. In a more precise definition, the elastic material is the one that returns to the original configuration when the external actions are removed. In addition, you may notice that there are objects that are more difficult to squash. As an example, a bicycle tire can be stretched more easily than a car tire. Although the two objects are made of rubber, car tire is thicker than bicycle one: this makes the first stiffer than the second. The stiffness is the capacity of the object to oppose to the forces acting on it: the deformation of a stiff (or rigid) beam is smaller than the deformation of a flexible one. Last, but not least, the ideas of ductility and fragility emerge. A *ductile* material is the one that requires to be largely stretched when it is broken; on the contrary, a material is said to be *fragile* if it breaks suddenly, i.e., without appreciable stretching. The concept of ductility, valid at the material level, can be extended to the structural level and in this case the capacity of a structure to avoid brittle collapse under damage and external stresses is named *resilience.*
With the overall target of providing resilience to sociotechnical organizations, *consequence-based design* tools need to be developed for risk analysis and management of enterprises and institutions. Specific approaches must be individuated, depending on the size of the system and on its peculiar organization. Consequence-based approaches are not currently considered by management theories and by most of the economic activities. We strongly believe that they should be included in the design and management of sociotechnical organization, exactly like engineers do for the design of aircrafts, ships

and bridges. The resilience of the system can be dramatically enhanced in this way and, whatever the size of the system, a more robust behaviour can be achieved.
Finally, we need to optimize the consequence-based approaches by means of the strategies of Nature. Natural structures, in fact, thanks to the evolution process, have optimized their behaviour with respect to external stimuli and have implemented complexity at its highest degree of efficiency. We will consider for instance the limits to growth of natural systems, the redundancy and compartmentalization strategies of plants and skeletons and the ductile/self-healing characteristics of natural tissues, which permit to tackle unexpected dangerous situations without evolving into global collapse. Inspiration from Nature will lead to innovative efficient strategies for managing more robust organizations in the social and economic environment.

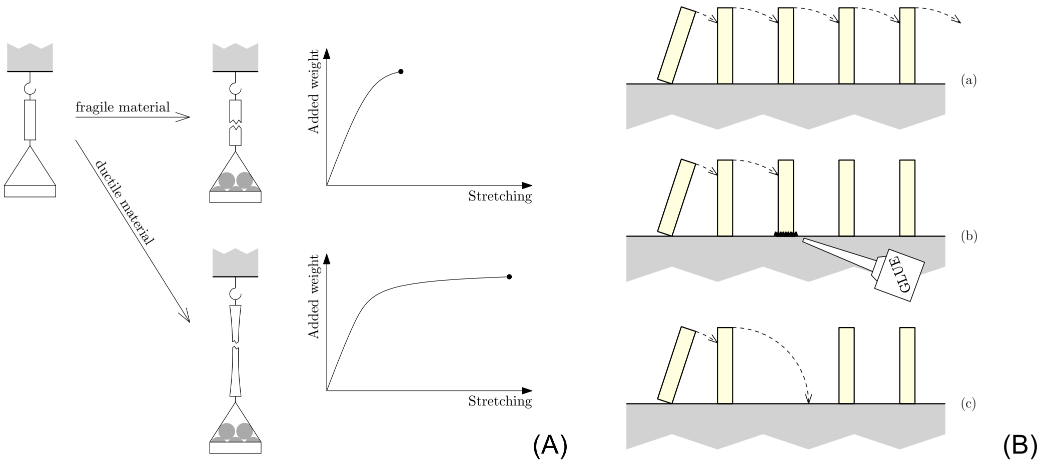

Fig. 1: In (A), a simple experiment illustrates the difference between fragile and ductile material. The test consists in adding weights in the lower basket up to the rupture of the material. If the material is fragile, at rupture the stretching is small. If the material is ductile, at rupture the stretching is large. Notice that rupture occurs when the same quantity of weights is added in the underneath basket, i.e., systems may show different response under the same external conditions. Subfigure (B): in (a) an example of progressive collapse, i.e., cascade failure, is sketched: when the leftmost domino tile is moved, it collides against the second one and so forth. Two strategies for preventing cascade failure are pictured. In (b) the introduction of a strong element (the glued tile) stops the propagation of the movement. In (c) the compartmentalization of the system is shown: the collapse on the left of the system cannot propagate to the right side.

3. Progressive collapse of the economic system: fiction or reality?

"According to the late reconstruction of the facts, all started in a May afternoon at Marvin and Phoebe Sellers' house, Camino de Palmas 4011, Tucson, AZ. It was Friday and Marvin Sellers was checking the balance of its accounts. The decision that would have changed history took about one hour". This is the *incipit* of the novel *"Depression or Bust"* by M. Reynolds [9]. After a discussion with his wife, Marvin decided against buying the new refrigerator he had ordered, because he worried about his money. When Jim Wilkins, the owner of the appliance store, heard about the order cancellation, his immediate reaction was to call the agent in Phoenix and cancel the request of 3 new refrigerators *"…because of large unsold merchandise"*. Then, just after this phone call, Jim *"… who had fallen in a blue mood…"* called Bill Waters, the car vendor in his town, and cancelled the order of a new car. After this call Mr. Waters, *"… feeling that a general tendency was growing…"*, asked his secretary to call the Buick sales office in Denver to cut the monthly car supply by two cars per month. And just after that, he called his real estate agent announcing the decision to postpone the purchase of a new house. A few days after, Marvin Sellers, who was a carpenter, was fired by his company, which had lost the construction job of the new Bill Waters' house!
The most important lessons of the satire are the following. The first is the amazing connectedness of the economic system. Due to globalization and technological innovation, all business sectors are connected via direct or indirect links, and finance pervades the system throughout with ubiquity and speed. Propagation of any stimuli is random and uncontrolled as they spread through the system incredibly fast. Remarkably, this is not fiction but everyday reality, and represents one of the drawbacks of the modern *liquid society* [10], not adequately taken into account by current socio-economic models.
In fact, the second lesson, which is a consequence of the first, is the domino-like cascade failure (Figure 1-B), that is, the progressive amplification of a small-scale event to larger and larger scales, up to the global one.
The exponential increase of links between firms, enterprises, institutions and individuals provides redundancy to the system but also favours rapid propagation of perturbation effects to the global scale. Exactly as a snow avalanche may originate when triggered by very small perturbations, the decision not

to purchase a refrigerator produces negative consumer reactions leading to production stagnation and global recession at larger and larger scales. Edward Lorenz, the father of the modern theory of chaos, wondered *"… will the flap of a butterfly's wing in Brazil set off a tornado in Texas?"*.

4. Weakness of large organizations: too big to fail or to survive?

When the World population will become larger than 20 billions people, there will be at least 2 or 3 billions of new western style consumers. Due to growing market opportunities and to increasing competition in many business sectors, the tendency to increase the size of enterprises and banks will continue. The operations of merging and acquisition testify the need to attain a certain *critical mass* for many businesses (e.g., automotive, air transportation and energy distribution sectors).

In mechanics it is well known that the main cause of large systems fragility is represented by the so-called *size-scale effect*. Galileo early in 1638 noticed that elephant's bones are intrinsically more brittle than cat's bones, although the constituent bone material is the same for all vertebrates (that is, calcium carbonate). At the beginning of 19^{th} century the maximum possible height of a tree was calculated based on the mechanical characteristics of the wood and on the buckling limit of rods. All living beings automatically regulate their growth up to a specified limit corresponding to the virtuous balance between the energy necessary for growth and functioning, and the energy that can be assimilated from nourishment [11]. Engineers know that <u>structures, as their size increases, dangerously tend to brittleness</u>. The theories of fracture mechanics explain this tendency alternatively deterministically (e.g., according to the growing strain energy which drives crack propagation) or statistically (e.g., according to the probability of critical defects of the microstructure) [12]. However, in any system, as system size increases, propagation of local shocks of any kind occurs more and more rapidly and tends to extend to the global scale (total collapse) instead of remaining confined locally.

A topological consequence of growth is the progressive unbalance of the ratio between the "volume" of the system and the "area" of its boundaries. This ratio increases with system scale, and this can explain, for instance, why small kids dehydrate faster than adults and why small animals in cold climates need thicker furs than larger ones. In economics, the above reasoning explains why, in relatively small organizations, the external exchange dynamics are more efficient than in the case of large organizations permitting a faster permeability and tendency to adapt to external stresses and stimuli.

The progressive weakening of companies and banks, which in the last decades largely grew through merging and acquisition strategies, is crystal clear. Good management and financial practices were often abandoned in the name of irrational or at least uncontrolled growth. Therefore, we are not surprised at the fragility of big enterprises, even under relatively small stimuli. As an example we quote the cascade effects following Lehman's Brothers collapse in 2008 and the subprime bubble highlighted the fragility of the world-interconnected financial system. Interestingly, analyses carried through the years 2008-2015 showed that small institutions reacted better and faster to the effects of the crisis [13].

On the other hand, some institutions (especially banks) have been considered of critical importance to become recipients of beneficial financial policies from governments or central banks (the Troubled Asset Relief Program (TARP) was established in the U.S.A. for this purposes). Proponents of this theory believe that some institutions are so important that they should become recipients of beneficial financial and economic policies from governments or central banks. Some economists believe that economies of scale in banks and in other businesses are worth preserving so long as they are well regulated in proportion to their economic influence, and therefore that the *"too big to fail"* status can be acceptable. On the contrary, other economists say the giant banks must be broken up. Still on April 2014, the International Money Fund warned that the problem of banks seen as *"too big to fail"* is still unsolved.

The limits to growth in the economic context have been investigated by the Rome Club since 1972. In the Meadows Report [14], they examined the five basic factors that determine, and therefore ultimately limit, growth on Earth - population, agricultural production, natural resources, industrial production, and pollution. Intrinsic limits to exponential growth were clearly stated, and the transition from irrational growth to global (dynamic) equilibrium was wished for. In the general frame of economic crisis and resource shortage, inspired by early ideas of counter-productivity and diseconomy, theories of de-growth claiming the downscaling of production and consumption are becoming more and more popular.

We have noticed that a general theory concerning the optimal growth and robustness of large organizations is missing in the current state-of-the-art. Regarding the classical theories of *economic growth*, both endogenous and exogenous models (e.g., AK model vs. Harrod-Domar model) do not give evidence of the tendency to brittleness of large organizations. Most of the recent studies have been oriented to specific business sectors, thus missing the intimate features of the problem. For example, Pamolli and colleagues [15] carried analyses of processes of growth at different levels of aggregation in the context of disordered systems and random processes. Attention was focused to the economics and policy of pharmaceuticals and health systems in Europe, and to the growth of business firms, leading to a scale free model for the firms' network.

5. Fragility of populations

In order to make other analogies between disciplines let us consider the way we are connected to the internet: glass fibers connect our Wi-Fi routers to the servers. Such thin cable-like objects are very flexible and very strong. Now, let us consider a cup for drinking, made of glass, i.e., the same material of the fibers: if it falls on the ground it breaks. How it is possible? It happens because as much as their size increases, materials that seem ductile and deformable at micro-scale become more rigid and brittle. Despite the simplicity of the previous example, the fragility in large systems is not new in science and sociology. Thinking about ancient civilizations (like, e.g., the Egyptians, the Roman Empire, the Maya, the Aztecs and, recently, the Soviet Union), societal collapse was certainly triggered by environmental or climate changes, hostile neighbors or trade partners and by progressive resource consumption. However, all the above causes are not sufficient to explain the (relatively fast) collapse, as noticed by Diamond [16], since *the response that different societies had to such threats was the crucial point*.

Diamond also suggests that, today, people collectively face many of the same issues with possibly catastrophic near-future consequences to many of the World's populations. In the context of developing countries, the Organization for Economic Cooperation and Development affirmed that "state building" is the central objective for international partnerships in situations of fragility. The long-term vision is *"… to help national reformers to build effective, legitimate, and resilient state institutions, capable of engaging productively with their people to promote sustained development"*. We are convinced that political fragility has multiple underlying causes and it can produce multiple consequences like vulnerability to internal conflict, inability to cope with humanitarian disaster and high risk of state collapse.

Thus, the response of human organizations against extreme external stimuli may be very different. As an example, consider the unexpected capacity of the Vietcong people to survive the American army (and the harmful effects of the forest). The heavy bombing made by B-52 between 1968 and 1970 did not kill any military chief among the Vietcong, and the ground operations were always favorable to the locals. On the contrary, the Spanish conquest of the Aztec empire easily occurred although many soldiers of the Cortés expedition of 1519 had never seen combat before and Cortés himself had never commanded men in battle before. Cortés smartly obtained support from a number of tributaries and rivals of the Aztecs, like the Totonacs and other city-states and even penetrated as a friend in the Montezuma's entourage.

Current state-of-the-art provides only partial explanation for these historical events. On the contrary, we believe that the *mechonomics* analogy can give new insights on them. Borrowing terms from structural mechanics, the behavior of the Vietcong can be defined "resilient", whereas the response of the Aztec to the external attack was "fragile" (further details on such terms are given in the following). A fundamental aspect is represented by the activation of internal weakening mechanisms, within the Aztec population, strengthening the invaders, which were not activated in the case of Vietnam. These mechanisms are analogous to those inducing cracking cascade effects inside a stressed solid, at the micro- and nano-level. The micro-defects and cracks, driven by the external supply of energy, begin to coalesce and, at the end, lead to the fracture of the structure. The resilient behavior of the Vietcong population was mostly due to their strategies of *compartmentalization*, which prevented cascade failure (see Figure 1-B).

In April 1968, a group of thirty individuals gathered in the Accademia dei Lincei in Rome; they founded the "Club of Rome", an informal organization initially aimed at examining the complex of problems that occurs to some degrees in all societies and that contain interacting technical, social, economic and political elements. The first study on the predicament of mankind [14] showed that, even if technology pushes to new discoveries and efficient uses of energy, unlimited resources do not appear to be the key for growth in the world system. In a recent updated study [17], the prices of the resources in a deeply interconnected system are the switches for the survival or the collapse. As the prices rises, geologists would find further resources, biologists begin to squeeze more and more from the crops, and so forth. Apparently, the only sustainable scenario is the one in which powerful technologies for pollution abatement, land yield enhancement, land protection, and conservation of nonrenewable resources are implemented. This would ensure stability in the population and better life expectancy.

6. Network topology: implications for system behavior and failure

Many businesses and organizations are structured as networks. A possible cause of default of large organizations can be found in the wrong design of the network operations that are put into place for logistics (see, e.g., component production, goods distribution, marketing and sales network). For more than 40 years, science treated all complex networks as being completely random. Recently, attention has been drawn to the topology of the network and its behavior with respect to all failure events has been investigated accordingly.

All networks are made of interconnected nodes and the nature and distribution of the links defines the network topology. The two more important classes of complex networks are the random *"homogeneous"* networks and the *"scale-free"* ones, see Figure 2-A. The homogeneous networks consist of nodes with randomly placed connections where most nodes have approximately the same number of links. There is a *democratic* distribution of connection and all nodes have the same importance. Examples of such networks are the highway networks in US and the network of hospitals in densely populated nations like Italy and Japan (i.e., hospitals uniformly distributed across the territory).

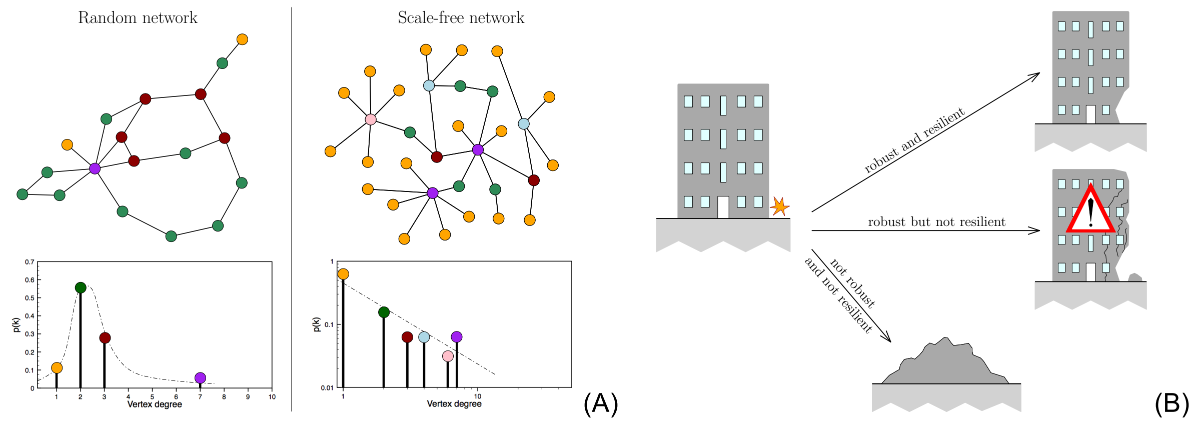

Fig. 2: Subfigure A: the structure of a random and a scale-free networks are compared. In random networks (left-hand side sketch) there is a characteristic vertex degree (in this case equal to 2) that is more frequent. In scale-free networks (right-hand side sketch) there is not a characteristic vertex degree: the nodes with few connections are more than those with many connections (called hubs of the network). In (B), three possible scenarios if a bomb explodes close to a building. If the building is robust and resilient, the explosion causes a damage which is strictly confined to the area invested by the injurious phenomenon. If the building is robust but not resilient, it does not collapse, but the damage caused by the explosion entails cracking and further damage spreads in the building. If the building is neither robust and resilient, the explosion causes the global collapse, i.e., the total destruction.

On the opposite, scale-free networks present a hierarchical structure containing *hubs*, i.e., nodes with a very high number of links. In such networks the distribution of linkages follows a power law in that most nodes have just a few connections and only a few have a tremendous number of links. The system has no characteristic scale. Examples of such networks include the European airline system (with hubs like the Frankfurt, Paris and London airports), the World Wide Web or the energy distribution system of France (with 19 big nuclear plants producing 77% of electricity in the country).
The accidental failure of a number of nodes in a homogeneous network can break the system into non-communicating islands. These network, thus, suffer for randomly distributed failures. In contrast, scale-free networks are more robust in face of such random failures. But they are highly vulnerable to a coordinated single attack against their hubs [18]. Therefore, adopting a scale-free network topology can be convenient and robust as long as the safety and security of the hubs are guaranteed. Consider, e.g., the world-wide consequences of a hacker attack to Paris Roissy airport, as compared to the negligible effects (outside France) of closing for some days Bordeaux airport.
In the case of enterprises and institutions, the network topologies show different characteristics also depending on their growth history. Of course, older nodes have greater opportunities to acquire links. Interestingly, we have noticed that public institutions tend to possess homogenous network organization, whereas private companies and businesses normally select scale-free arrangements. Another tendency is the polarization of the job market into two systems, one scale-free network comprising a few hubs (high qualified and well-paid jobs) and one homogeneous network made by many low-level occupations. Polarization, as argued in recent times, is leading to the disappearance of the middle-class.
According to the state-of-the-art, *many sociotechnical organizations have not been designed with adequate "protections" for their topology*, and a number of inefficiencies and failures can be explained by this negligence.

7. Black swans and unpredictable events: the need of robustness

History tells us that unexpected events may occur creating surprise. After Willem Janszoon's discover in 1606, a similar belief had been certainly experienced by the first ornithologists across Australia when observing the *Cygnus Atratus*, alias a *black swan*. In the Old Europe, people were convinced that all swans were white; an unassailable belief as it seemed completely confirmed by empirical evidence.
This proves that a learning process based on pure observations has limitations, as already pointed out by the famous *inductivist turkey* [19]. Just one observation can invalidate a general statement derived from millennia of confirmatory sightings of millions of white swans. This example can be framed in the category of *"black swan"* events [20]. Such situations may also be considered a subset of a wider epistemological problem, that is, the problem of the "*unknown unknowns*". Black swans are the unexpected

events, which have not been considered at the time of the original design of a certain system until they appear for the first time. The concept of black swan is accompanied by the problem of *weak signals*, which we often fail to foresee when carrying risk analyses or stress tests upon companies and human systems.
Black swans and weak signals, from a statistical point of view, are related to the broader *tail problem* of probabilistic distributions. Silver [21] states that there are systems that are inherently chaotic and are characterized by unpredictability.
In engineering, the term robustness relates to the capacity of a structure not to suffer disproportionate damage under unexpected events. In other words, damage occurring at a local scale must not trigger the (global) collapse (see Figure 2-B). Engineers have found various strategies to provide robustness to a structure, mainly by playing on the ways the loads are transferred through the various part of the structure (e.g., redundancy) or inserting structural fuses (e.g., crack arresters) in order to *compartmentalize* the system [22]. A robust system is able to develop plastic mechanisms without compromising the overall structure, which does not collapse.
Resilience relates to the capacity of the system to accommodate the (unexpected) external loads and to deform elastically. Because of the basic meaning of the concepts, the term "resilience" is well diffused in other disciplines. In sociology and psychology, resilience is defined as an individual's ability to properly adapt to stress and adversity. In engineering terms, in order to have robust systems, resilience goes hand-to-hand with stiffness. The stiffness of a system is its capacity to deform once subjected to external loads. The larger the stiffness is, the smaller the displacements are.
We believe that the above concepts of robustness against unexpected events can be applied also to banks, enterprises and public institutions, especially now when they are nodes of a global network. For instance, Europe is starting to be worried about resilience and robustness of engineering, economic and social systems. In fact, the Central Bank is performing the so-called *"stress-tests"* on the principal banks, and the Horizon2020 funding program includes a number of research calls concerning resilience of critical infrastructures under accidental events. The response of sociotechnical systems to unpredictable stimuli can be very different and may lead to failure or to positive counter-reactions depending on their internal organization, on their capacity to absorb and distribute the external stresses and on the ability to direct the energy toward appropriate channels.
The capacity of a system to tolerate damage and changes is, in fact, a key property for the survival and the success. The response of a system to an external unexpected event can be described through two different concepts: robustness and resilience. The former refers to the capacity of an entity not to be disproportionately damaged when an error occurs. In civil engineering, as already mentioned, the robustness is the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause. To make a comparison with computer sciences, a robust software cannot crash when a wrong input is given.
On the contrary, resilience refers to the capacity of the system to cope with change. A clear definition of resilience in organizations is given by BS65000 as the *ability of an organization to anticipate, prepare for, and respond and adapt to incremental change and sudden disruptions in order to survive and prosper*. Hollnager, discussing about systems, states that complex entities are dynamic and, in the majority of their life (e.g., the operations in a society), they are in a stable state. But, because of the continuous external stimuli, the dynamic stability can turn into a dynamic instability. In such situation, a resilient system must be able to respond to changes and challenges without losing its control. An example of a resilient system able to cope which changes is given by FedEx in the US. Night flights connecting the regional hubs to the central hub are only 60 percent loaded. This allows the aircrafts to be diverted to other destinations in order to recover "at risk" cargos and ensure the quality of the service to the stakeholders.

8. Consequence-based design or design thinking against the fragility of sociotechnical organizations

As a general methodology, we argue that the fundamental rigorous approach of structural mechanics can be transferred to sociotechnical organizations. The methodology will be split into the following well-established frameworks (and others may be considered):

- Application of the linear theory of elasticity and visco-elasticity;
- Application of nonlinear theory of plasticity and softening;
- Application of the theory of fracture mechanics;
- Application of the complexity theory;
- Definition of consequence-based models for enterprises and institutions;
- *Biomimetics*, i.e., model inspiration from Nature [23].

As in structural engineering, the basic considerations in *Mechonomics* must be done bearing in mind the concept of elastic material. Elasticity is a basic property of solid materials. Applying a force A upon a solid body, deformation arises, e.g., for stretching a rubber it is necessary to apply a force. An elastic body returns to its initial shape after removal of the external forces. In particular, if under an increase of the force a proportional increase of displacement R occurs, the material is said to be linear elastic and the constant of proportionality is the elastic (or Young's) modulus K, representing the stiffness of the material:

$$R \text{ (response)} = K \times A \text{ (action)}$$

Linear elasticity is the behavior of the majority of solid materials at low loadings. Living tissues, like e.g., the skin of human body exhibits nonlinear elasticity, as the stiffness K is not constant but progressively increases. This behavior gives rise to the so-called *J-curve*, which represents the constitutive behavior of most living materials. The properties of the J-curve are truly remarkable, as the progressive increase of the stiffness means that the internal stored energy (the dashed area under the curve) is kept very low although deformations can be very large. Low stored elastic energy implies good safety against rupture under unexpected events. In any system, the elastic-like behavior can be looked for when considering a dependent variable's sensitivity to a change in another (independent) quantity. In human-based systems, the elastic-like behavior can be achieved when positive counter-reaction mechanisms R and additional energy resources are present in the intimate organization. An example is the capacity of a manufacture plant to satisfy the growing demand for goods by increasing the production capacity R according to the increase of the demand A. Of course, on the opposite side, when the demand decreases the company must be able to reduce production without permanent consequences on its functioning regime (i.e., without discharging some people from employment nor dismissing production plants).

Although the above behavior may appear as expensive and inefficient, this is not the case, as the dormant production energies can be usefully applied on parallel tasks, provided a beneficial flexible workforce organization is put into play for example in smart factories in which objects can be tailored and 3D printed on-demand. We have stated that a principal cause of fragility of large systems is represented by the so-called "size-scale effect". The intrinsic weakness of companies and banks, which in the last decades largely grew through merging and acquisition strategies, is crystal clear. Good management and financial practices were often abandoned in the name of irrational growth. However, in many business sectors, a minimum critical mass is important for competing in the global market and therefore the problem of system size cannot be merely simplified.

Sociotechnical systems are usually not able to adapt dynamically their internal organization to external stimuli, to face unexpected scenarios, they should be designed to be robust. A robust system is able to develop plastic mechanisms without compromising the overall structure, which does not collapse.

Structures made of elements in parallel have shown that the presence of preponderant elements largely affects the overall behavior once damaged: a slight variation of their properties implies large consequences on the entire systems. In this sense, in the perspective of designing a robust system it is, thus, better to have equally important elements in it. At the final stage of damage, that is, when the element is totally removed, the impact on the system depends on the value of the complexity. Structural complexity measures the interaction the structural elements have in a structural scheme (i.e., a set of columns and beams) [24]. As much as the complexity reduces, i.e., there are preponderant elements in the construction, the average effect increases dramatically. For complex systems, i.e., where no preponderant elements are present, redistribution mechanisms are present when a part is removed. Size effects play a key role: the larger the number of elements, the higher possibility of redistribution exists [25]. These observations are valid at various scales. At a large scale, e.g., in material science, it is well known that microstructural disorder and complexity provide toughness to the materials.

In order to provide robustness to large organizations, we suggest to use the approach of *consequence-based design (CBD)*. The concept of consequence-based engineering was developed in the framework of earthquake engineering with the purpose of finding alternative strategies to reduce seismic risk [26]. The problem was that seismic hazard mapping (and the corresponding building rules) are based on statistical analyses of historical earthquake events, and thus it is not possible to exclude events of magnitude larger than the maximum expected one (i.e., black swans, as the quake occurred in Japan, 2011).

The basic concept of CBD is that, before any engineering calculation, the estimate of all the possible consequences to adverse events should be carried out, independently of the expected loads and external stresses that can act upon the structure according to building codes.

The designer, before any engineering calculation, estimates the possible consequence on the system after a failure on one of its parts. The attention is shifted from the effects of the external stress on the element on the consequences on the whole system. This approach, called *consequence-based-design*, does not require a complete definition of the hazards on the system and, thus, is suitable for resilient and robust design. Until Sept. 11, 2001, consequence-based methodologies were restricted to nuclear engineering or particularly strategic infrastructures.

A four-step decision tree can be adopted to determine if: (a) estimated consequences are acceptable, (b) if acceptable consequences should be redefined, (c) if modelling parameters should be refined and (d) if further interventions should be considered. If anticipated consequences exceed tolerable ones, and no further redefinition of acceptability is feasible, parameters defining the hazard can be refined to reduce anticipated losses (assuming that the preliminary analysis were conservative), and/or system

interventions can be prescribed for the same purpose. Iteratively, consequences will be estimated for a number of different intervention strategies with various input parameters describing the hazard.
Since the consequence-based approach deals with the effects of an event rather than with its causes, it is suitable for dealing with black swan events. Following Nafday [27], a two-stages process can be applied for analysis or design of a robust organization through CBD. In the first stage, the system will be designed following the common rules and using the current methods, providing appropriate minimum redundancy, continuity and inter-member ties. Afterwards, the components of the organization will be selectively redesigned for ensuring adequate fault tolerance and integrity, based on their role and importance in contributing to adverse consequences. These consequences can either be the system collapse or any other pre-defined performance criterion. In other words, local events will be randomly applied to the components of the organization, simulating all possible negative consequences, and the residual capacity of the system will be evaluated. Capacity requirements for each component will be quantitatively upgraded following their specific role in contributing to pre-defined adverse consequences. The concept of *member consequence class* [26] will permit to differentiate component requirements based on their role within the organization. The basic idea is to control the consequences of a failure to minimize the risk. The consequences of failure of a certain member can thus be limited. Even if the size of an enterprise has to be large for some reasons, a number of strategies to increase its resilience can be borrowed from engineering. *The results of the consequence-based methodology* will be, for instance:

- to increase the toughness of each component of the system by providing ductile characteristics at all hierarchical organization levels [28];
- to provide guidance to design the organization with redundancy and include alternate load paths capable of by-passing the failure or inefficiency of specific components [29][30];
- to prefer and select parallel task arrangements to serial arrangements whenever possible;
- to optimize the system division into a series of mutually independent entities (i.e., compartmentalize the system by means of fuse elements between business units and areas) so that local stress and damage events are not transmitted from one entity to the closer ones;
- to design counter-measures to network failures based on the topology (e.g., for a scale-free organization put specific attention to the hubs);
- to exploit complexity at all levels to provide anti-fragility to the internal processes [24],[25],[26][31][32][33].

The above strategies are inspired by the evolutionary processes of Nature, which have provided living beings with adaptability and optimal performances against unexpected events.

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