Risk Governance

A framework for risk science-based decision support systems

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Abstract

The present article synthesizes a general approach to the development of risk governance decision support systems, based upon the interdisciplinary dialogue between risk science and the complexity sciences. A conceptual review of risk science and the three main schools of the complexity sciences (the Santa Fe School, the Stuttgart School and the Brussels-Austin School) is provided and addressed with regards to the new challenges faced by organizations in their need for adaptation to interconnected risk situations and the dynamics of risk in networks.

Keywords: Risk governance, decision support systems, risk science, complexity sciences.

1. Introduction

Risk is, currently, a central strategic problem for human organizations that face interconnected risk situations, difficult to quantify in their dynamics and threatening to the future sustainability of organizations (Hayashi *et al.*, 2012). Risk can no longer be addressed in a reductionist approach, measuring each risk source separately and considering relations in terms of static correlation structures.

The linkages between risk situations change, risk sources can interconnect in unpredictable ways, nonlinearities and explosive dynamics, typical of nonlinear complex networks, can alter overnight strategic assumptions and strategic goals, invalidating an organization's strategic choices, and demanding of the organization the need to quickly adapt to the new strategic situation, more than often in contexts with insufficent data and calculatory basis (Hayashi *et al.*, 2012; Bremmer and Keat, 2010; Guilhou and Lagadec, 2002).

The development of risk governance has become an organizational strategic urgency (Bremmer and Keat, 2010). Organizations must develop a risk governance structure able to: (i) *promote integrated strategic risk management within the organizations, as a fundamental part of their strategic planning*; (ii) *guarantee that threat assessment and emergency procedures are in place* and (iii) *assure a functioning and effective risk sources' monitoring system*. Only in this way can organizations develop the resilience that they need to be able to face today's risk situations.

Supporting organizations in this effort, providing concepts and tools towards risk management, are three transdisciplinary fields: risk science and complexity sciences. The current article provides a risk science-based methodological approach to decision support systems for risk governance, resulting from the conceptual synthesis of risk science and the three major schools of the complexity sciences: Santa Fe School; Stuttgart School and Brussels-Austin School.

In **section 2.**, a review is made of different perspectives on risk and organizations, developed from risk science. In **section 3.**, a brief conceptual review of the three main schools of thinking on complexity is provided, in connection with the problem of risk and complexity. In **section 4.**, the new context that current risk governance faces is reviewed, in particular in what regards the interconnectedness of global risk situations, and decisional tools and approaches are synthesized from the previous sections' work. In **section 5.**, main conclusions are drawn in the form of a methodological approach to support organizations in building up risk governance decision support systems.

2. Organizational perspectives on risk and risk science

The interconnected nature of risk that characterizes the current decisional framework of human organizations has brought about the need to readdress the notion of risk, into a workable notion that allows for the effective development of risk management tools even in unstable dynamics, for which large samples of historical data, in many instances, no longer provide for enough elements to anticipate sudden changes in probability profiles.

Assessing risk in complex organizational frameworks that characterize the current world system has demanded of organizations a return to the foundations of scientific thinking on risk, and, in particular, to clearly distinguish between the identification of risk sources and exposures from the measurement toolbox used to assess/quantify risk.

Risk science and the complexity sciences address such a foundation and make such a distinction, grounding the notion of risk in its conceptual root in the Medieval Latin term *resicum*, that synthesized three notions: danger/peril (*periculum*), opportunities (*fortuna*) and uncertainty (Gonçalves and Madeira, 2010). Thus, in risk science, risk is considered to be present in a systemic situation whenever there are threats and/or opportunities and uncertainty. It is up to risk measurement, then, to identify the threats and opportunities and to quantify the uncertainty (when possible).

A systematic treatment of risk, developed from risk science, needs to clearly distinguish three phases of strategic risk assessment, which can be synthesized as follows:

- **Identification of the presence of risk:** involves the recognition of the exposure(s) to risk by the organization, the identification of the risk sources and of the linkages between the different sources;
- **Evaluation of consequences:** mainly tackled through scenario analysis and loss analysis;
- **Measurement process:** calculating an appropriate risk measure.

We call this RCM approach (***Risk Consequence Measurement approach***). Applying the RCM approach, one can see that classical decision theory becomes effective whenever, in the R phase, the exposures can be completely laid out, in the C phase, the set of consequences can be exhaustively identified, and, in the M phase, probabilities can be assigned to each consequence, in this way, risk assessment and management is amenable to a quantitative scheme based upon traditional risk measurement theory, this is, however, only possible in systems with very specific dynamical processes, but it may breakdown once we deal with interconnected risk scenarios, a major point that will be in the next section, regarding the Santa Fe School and the *risk of changing risk* problem.

Systemically, two conceptual extremes can be preliminarily assumed, as a working basis, to understand the different sources of risk in organizations: the risk coming from *exogenous shocks* and the risk generated by the *system's dynamics* (Boldrin and Woodford, 1992).

In linear systemic contexts, the accumulation of *independent exogenous shocks* allows one to address an evaluation of risk centered on a notion of probabilistic stability, dominated by a discourse in turn of *averages* (Prigogine and Stengers, 1986; Prigogine, 1962): the averages of the relevant systemic variables and the average dispersion in turn of these averages (notion of standard deviation). Organizational goals and risk management solutions should, then, address intended values for average exposures, properly discounted for risk.

The scientific fundament for this approach to risk can be located in the *principle of order of Boltzmann* and in the *law of large numbers* (Prigogine and Stengers, 1986). Under the *principle of order of Boltzmann*, the average activity of a population corresponds to a leveling over the individual behaviors, such that the mean is representative of the population (Prigogine and Stengers, 1986). Under the (strong) *law of large numbers*, the mean of a sequence of independent and identically distributed random trials converges to the expected value, almost surely, when the number of trials tends to infinite (*thermodynamic limit* for populations or statistical ensembles).

The *principle of order of Boltzmann* and the *law of large numbers* are both based upon an incremental arithmetic thinking about risk, worked from the notion of noise and the additive accumulation of random shocks. This thinking on risk is, in particular, supported by another theorem (the *central limit theorem*), under which the sum of independent random variables with finite mean and variances tends asymptotically to a Gaussian distribution, for many general probability distributions of the variables in the sum.

Together with the *principle of order of Boltzmann* and the *law of large numbers*, the *central limit theorem* influenced a working assumption that any dynamics, in strategic variables, relevant for an organization, could be modeled as arithmetically decomposable in a regular behavior added by a noise term with probability increasingly negligible for fluctuation values far from the mean, in accordance with the Gaussian mesokurtosis (Prigogine and Stengers, 1986).

Chaos theory exposed, however, the possibility of occurrence of patterns of dynamical complexity signalized as random but generated (deterministically) by the systemic activity itself. Chaos theory, therefore, opens up, for risk science, the theory of endogenously generated risk, which comes from the fact that the systemic dynamics can be generative of risk, even in the absence of dynamically relevant exogenous shocks (Lorenz, 1995; Boldrin and Woodford, 1992).

The emergence of chaotic patterns can be approached from three dynamical properties: the exponential divergence of small neighborhood intervals of any trajectory; a dense collection of cyclic trajectories and the mixing behavior (Peitgen, *et al.*, 2004).

The mixing behavior implies that the system's trajectories visit the neighborhood of each periodic trajectory in a dense collection of periodic trajectories (the denseness means that each chaotic trajectory has, in a small neighborhood, a periodic trajectory), the exponential divergence, in turn, leads to dynamical instability with regards to each periodic trajectory, in such a way that one can approach the chaotic dynamics, in the system's dynamics, in terms of permanent jumps between unstable periodic trajectories (Bradley and Mantilla, 2002).

The exponential divergence with respect to any neighborhood interval of any state at any given time leads to an exponential divergence of trajectories initially close to each other, this dynamical behavior is known as *sensitive dependence on the initial conditions* (Lorenz, 1995) and it is a source of uncertainty given finite limits in the reading and registering of any initial condition. On the other hand, a system with chaotic dynamics but also subject to exogenous shocks (*chaos with noise*) is such that: any small fluctuations coming from exogenous shocks are exponentially amplified (*butterfly effect*), so that even weak exogenous shocks alter irreversibly the future dynamics of the system (Lorenz, 1995).

The chaos with noise models influenced the development, during the decades of 1980 and 1990, of a scientific thinking on risk in the organizations that defends that any organization must evaluate the risk associated with external unpredictable elements, but approachable from a dynamic incrementality (*arithmetic risk*), and, simultaneously, it must evaluate the risk associated with the possibility of chaotic dynamics that are, themselves, source of risk and that may also amplify any term of exogenous noise (*geometric risk*) (Lorenz, 1995; Stacey, 1995; Morin, 1998).

Within such a scientific framework, risk management must take into account that dynamical instabilities and irregularities make part of what is the normal functioning of an organization, being linked to the processes of adaptive feedback that are proper of any complex adaptive system (Lewin, 2000). On the other hand, this very same *structural instability* was considered to be vital to the ability of the organizations to be continually creative and innovative (Stacey, 1992).

Chaos theory was seen as providing for examples of dynamics that allowed one to simulate a basic organizational proper (Stacey, 1992; 1995): emerging unpredictability with patterns of order in randomness that show persistent dynamical structures, sustained by the vital dynamical flow of the system, such structures were exemplified, within chaos theory, by *strange attractors* (Lorenz, 1995): invariant structures of the chaotic dynamics, identifiable from the geometrization of the dynamical variables' behavior, whose trajectory is situated in a bounded region of the system's geometric space of states (*phase space*), the resulting geometric figure of the invariant set shows a complex fractal geometry, composed by regularities and irregularities at different scales (Lorenz, 1995; Peitgen, *et al.*, 2004).

In the strange attractors there is, thus, a local dynamical instability and a global invariance, irregularity and structure at different scales (Peitgen, *et al.*, 2004). These attractors can, in this way, be considered as the geometric product of the adaptive dynamics of the systemic organization, mirroring the need for the organization to conserve a structure and simultaneously to anticipate and solve problems, changing its behavior with strategic agility (Prigogine and Stengers, 1986).

Another feature of chaos, also relevant for organization science, is the occurrence of feedback circuits at the level of the organization's performance evaluation systems and risk management systems, such that the evaluation of a certain result triggers adaptive responses towards future results which, in turn, must be permanently reviewed in a strategic planning process that must incorporate a notion of agility at the level of the definition of general and specific goals to an organization.

The feedback process, resulting from the strategic planning and subsequent monitoring is such that the projection about the future, developed by the organization, changes the strategic behavior of that same organization and, in turn, may change the future course of events.

Thus, any risk management system inevitably leads to an antecipatory feedback cycle, in which the expectation and the organizational adaptive actions function as connectors of the strategic motion from the anticipated/projected future to the permanently actualized future of the organization. This type of computation, more complex in its probabilistic formalization, is approachable within quantum game theory (Gonçalves, 2012b).

While chaos theory played a formative role with respect to risk science and to the perspectives on risk in the organizations, the wider field of the complexity sciences opens up conceptual tools and frameworks that may help risk science and risk management to address the current problems on risk governance that organizations need to face. To better understand this point, it becomes necessary to review, first, some of the major conceptual lines of each of the three main schools of scientific thinking on complexity.

3. The three schools of the complexity sciences and the problem of risk in the organizations

The complexity sciences developed from the paradigmatic basis of the second cybernetics, coming from the interdisciplinary and transdisciplinary works of the three main poles/schools: the Santa Fe School, the Stuttgart School and the Brussels-Austin School.

3.1. The Santa Fe School – adaptation and the *risk of changing risk*

The Santa Fe School resulted from the works developed in the Santa Fe Institute, born out of the Los Alamos National Laboratory, in the 1980s. In the Santa Fe Institute the organizations are approached as complex adaptive systems (Holland, 1995; 1998; Lewin, 2000). The Institute's research combines the theory of dynamical networks with nonlinear dynamics and adaptive computation (Lewin, 2000), which led, in the case of chaos theory, to a new class of models: the models of nonlinear dynamics and chaos in networks, whose theorization, case-based development and application to different systems (physical, biological and even social) is mainly due to Kaneko (Kaneko and Tsuda, 2001), who proposed coupled nonlinear maps as models of turbulence in the spatial and temporal dynamics of physical systems.

These models came to expand the main problem of the validity of the *law of large numbers*, which may not necessarily hold for coupled nonlinear dynamical systems (Kaneko and Tsuda, 2001). Indeed, in the statistical analysis of chaos in nonlinear dynamical networks, there can take place an instability in the probability distributions that may fluctuate in accordance with an emergent feedback process between the mean state of the system at each moment and the statistical distribution of states, that is, the mean state and distribution influence each other (Kaneko and Tsuda, 2001), a process that did not take place in the standard examples of low dimensional ergodic chaos, which made emerge invariant distributions (Prigogine, 2001).

Fluctuations and dynamical instability in distributions, linked to the adaptive behavior of complex adaptive systems and the nonlinear dynamical behavior of networks may provide for a useful theoretical basis to address the problem of instability in risk profiles, that is, the *risk of changing risk* (Doherty, 2010).

In the unstable settings, that characterize today's globalized and networked economies and societies, the *risk of changing risk* is a major problem for risk governance, and a major reason for its development. It becomes necessary to implement procedures and protocols to address unexpected sudden changes in risk profiles, in particular in what regards probability distributions (Doherty, 2010; Bremmer and Keat, 2010).

The *risk of changing risk*, according to Doherty (2010), opens up a major insurability problem, in this regard, the author distinguishes between a ***two-stage risk framework***: the ***first stage risk*** comes from changing risk profiles leading to unstable risk premia and fluctuating asset prices; the ***second stage risk***, on the other hand, is the insurable risk, that is, the risk associated with a loss taking place or not. First stage risk is, according to Doherty (2010), uninsured, while second stage risk is insured through short term insurance contracts. Risk management strategies, tools and policies will, then, have to deal with the definition of a reasonable, and perhaps changeable, short term predictable horizon and possible breakdown moments of that same horizon, over which contingency plans and other adaptive measures may have to be put into place, in particular, in regards to changing asset prices and risk premia.

One can illustrate well how network-induced exposures take place, in the financial case (Whitfield, 2008): as soon as toxic or high risk assets are introduced in many portfolios, and an expansive dispersion of the market for these assets takes place, then, all of the portfolios that did not invest in the high risk assets, but that have assets in common with the portfolios that did invest in the high risk assets, are still exposed to the risk of synchronized liquidity preference, that is, a great number of investors closing their open positions and selling not only the high risk assets but the other assets as well.

In this context, the adaptive problems that are worked upon in complex adaptive systems theory, may have to be expanded to deal with a risk coevolution process, since organizations have to adapt to a decisional context with "moving" decisional constraints and objective functions, so that organizations have to adapt to the decisional problems and to the risk that the underlying structure of those problems' changes, changing with it the exposure to risk, the consequence set and the probability distributions. This is a major challenge for both complex adaptive systems theory and risk science.

3.2. The Stuttgart School – anticipating the direction of the changing risk

The Stuttgart School of *synergetics*, under the influence of Hakken, works with self-organization processes that lead to the emergence of lower dimensional dynamics in high dimensional systems. One of the key operative concepts, on this matter, is Hakken's *slaving principle* (Hakken, 1977), under which a system with a high number of degrees of freedom is able to generate emergent dynamics described by a small number of dynamical variables that represent dominant active *degrees of freedom*, whose dynamics operatively enslaves the remaining degrees of freedom, as a result of a process of systemic self-organization.

For risk science, this school allows for an effective way to mathematically explore the *risk of changing risk* problem, since it allows one to address particular instances in which there may emerge slow moving degrees of freedom that come to act as control parameters and fast moving degrees of freedom that come to behave as order parameters, in this way, the system may undergo spontaneous and self-sustained phase transitions (Püu, 1997), which is a property in common with many current risk scenarios.

Synergetics offers, to risk governance, a relevant working tool: an organization should look at the risk sources for slow moving degrees of freedom, for these may offer a greater predictability and they are key drivers of change, so that the direction of *changing risk* may be anticipated to a certain probabilistic degree.

3.3. The Brussels-Austin School – the risk and complexity problem

The third major school of thinking about complexity is closely linked in its fundamental concepts to risk science, since it places risk as an underlying concept necessary to understand complexity. Human organizations are conceptualized as open systems that, to survive, have to expose themselves to risk situations, consuming resources and generating adaptive dynamics for their systemic sustainability, which, in turn, are generators of new risk situations.

The Brussels-Austin School was developed from Prigogine's works and collaboration with two institutions: *The Center for Complex Quantum Systems* (at the University of Texas) and the *Free University of Brussels*.

The conceptual basis on the relation between risk and the self-organization of complex systems results from the notion of *dissipative structure* introduced, within thermodynamics, by Prigogine and for which the author won the Nobel Prize of Chemistry in 1977. A *dissipative structure* is an open system that feeds upon energy and matter from the environment, dissipating energy in its self-organizing systemic activity (Prigogine, 1962).

In conceptual terms, the notion of dissipative structure synthesizes a dynamics of survival linked to processes of (eco)systemic management towards an adaptive sustainability in a permanent game of aggregation and disaggregation.

From a risk science standpoint, combining Varela's thinking with Prigogine's (Varela, 1997; Prigogine, 1962), one can work with the notion of *dissipative structure* as a system whose *autopoietic dynamics* leads to a survival far from a systemic regime of structural dissolution in a disaggregating flux (*self-organization far from thermodynamic equilibrium*).

Organizations, worked from the concept of *dissipative structure*, can be considered as generative of systemic risk resulting from the adaptive response of survival before permanent threats of disaggregating dissolution.

This notion of organizations generating risk as a result of their activity was also recognized by Beck ([1992], 2000), regarding the process of growth and development of current economies and societies, and synthesized by the author under the notion of *risk society*.

On a planetary macroscale, for the human system to work, it must consume energy and resources and this is a primary source of risk: resources must be consumed, energy must be generated and this places a pressure on the growth and development of the human system. Pollution, depletion of natural resources, environmental risk, all of the major environmental risks singled-out by the World Economic Forum (Hayashi *et al.*, 2012) can be linked to the nature of any complex system whose growth implies the production of risk.

On the other hand, human systems have developed to a point where risk management depends upon a market for risk, which is not limited to the insurance industry but has developed and expanded on a global scale due to the *derivatives market*.

The derivatives market allows a greater flexibility in risk management through complex hedging operations, on the other hand, the derivatives market leads to a risk economy where exposures to risk are transferred within the financial system.

One particular case was the subprime process of securitization of mortgage credit risk exposure, which fuelled the real estate market, but at the same time exposed the global financial system to that risk, through the exchange of high risk derivatives, whose risk impact was in some way hidden in investment funds (Whitfield, 2008).

The emergence of a risk economy implies a complexification of the *dissipative structures* notion, regarding the role of risk in the system's *autopoietics*, since the system is not only source of risk and must not only expose itself to risk situations in its living activity, the system is organized in turn of a risk and sustainability problem complexified by the dynamics of risk production, distribution/dispersion and consumption.

The interest in a certain financial asset, for instance, depends upon that financial asset's ability to repay its investors, and in order for an investment to yield high enough rates of return it must imply an exposure to greater risk. Investors with higher returns profiles are also "consuming" higher risk.

In order to address the complex interconnected nature of risk situations, risk science needs new effective tools. In this regard, the concepts of the three schools (Santa Fe; Stuttgart and Brussels-Austin) provide for a basic groundowork upon which one may build applications that can be effectively applied to the current more complex contexts. It is to this latter point that we now turn.

4. Tools for Risk Governance and the Three Schools

The three schools of complexity may help risk science establish a basis for addressing the current risk problems that human organizations face. Following the three schools, there are two main elements that must always be taken into account: (i) the interconnectivity between systems and (ii) the adaptive processes.

4.1. Interconnectivity and risk dynamics

The interconnectivity between systems has structural components that may change at a slower pace and dynamical components that may change more quickly (as shown by *synergetics*). Transportation networks, for instance, have a less fluid structure than the internet, in which websites are created, connected and closed down, such that the network is permanently changing. There are, however, elements in the internet's structure which are constitutive in the sense that they form building blocks that assemble the architecture upon which the internet is built, and there are elements in the internet's structure that have emerged from its dynamics and that may characterize the internet in a structural sense.

One example of the later is both the internet network and e-mail network topologies, which show a scale-free structure, characterized by a few hubs and a power law decay in the degree distribution (Ebel *et al.*, 2002; Barabási and Bonabeau, 2003). The hubs may facilitate the viral spreading of computer viruses, like the "I love you" e-mail virus, which infected, in May 2000, more than 500,000 individual systems around the world (Ebel *et al.*, 2002). Hubs are also preferred targets for cyberattacks, including, of course, those that want to spread viruses through the web. Affecting the internet traffic associated with a hub may affect the internet traffic of other target websites, denial-of-service attacks to hubs are, therefore, a considerable risk factor.

Scale-free networks are also present in human transportation systems, which are also vulnerable at the hubs. On the other hand, the hubs play a key role in keeping the networks functioning, because they are centers through which most of the circulating traffic passes through from one place to the other in the network, therefore, hubs play a fundamental role in a network's systemic sustainability.

Scale-free networks' examples illustrate that to address risk in complex dynamical networks one needs to address how the network is interconnected, in particular its topology, and how different topologies change the system's dynamics as well as the system's dynamical exposure to risk. The interconnectivity changes the dynamics because the dynamics proceeds from the connections, different connectivities may change adaptive behavioral patterns, for instance, depending upon the context, some network structures may be more resilient than others to certain environments and some may have particular vulnerabilities: the internet scale-free structure shows an adaptive agility, in particular in what regards the dispersion of data, news and knowledge, on the other hand, that same adaptive agility is based upon fast-paced rhythms associated with network dispersal mechanisms that are fueled by the hubs' traffic flow, this opens up the way for viral dynamics to take place.

Viral dynamics in the web, include the dispersion of spam, the dispersion of computer viruses, spyware, malware, and other related problems for computer security. On the other hand, viral dynamics also include, for instance, the dispersion of behavioral patterns and viral videos. Viral behavior patterns include, for instance, viral consumption patterns or even viral dispersion of financial risk, an example of which was the generalized exposure of the "financial web" to toxic securities, in the subprime crisis (Taylor, 2012; Easley, *et al.*, 2011; Bollier, 2009; Whitfield, 2008).

In evolutionary terms, viral dynamics are recognized as evolutionary accelerators, linked to processes of symbiosis and hybridization (Ryan, 2009). Independently of the particular cases of viral dynamics, there are general processes that can be identified and synthesized to a scientific research of these dynamics. Ryan (2009), in the context of evolutionary biology, identified the specificity of the evolutionary processes associated with viral dynamics by the term *virolution*.

The two central evolutionary processes of *virolution* – symbiosis and hybridization – can be conceptually approached in regards to the evolutionary dynamics that are proper of nonlinear adaptive networks that involve processes of adaptive contamination (Gonçalves, 2012a; Holland, 1995; 1998). At the level of human systems, the adaptive contamination involves an inter-agent synchronization with changes of behavioral and cognitive patterns, such that, when facing certain environmental pattern conjugations and adaptive situations, the adaptive agents tend to produce the same responses, thus, replicating a complex of behavioral patterns (Holland, 1995; 1998; Kaneko and Tsuda, 2001). Adaptive contamination is not reducible, in this way, to a simple behavior imitation, but, instead, to the integration of behavioral *schemata* that lead to complex adaptive responses, incorporated in new cognitive patterns (Holland, 1995; 1998).

Viral dynamics, in human networks, can be identified as taking place whenever there is a concentration, in a very short period of time, of the replication of the behavioral pattern, replication that becomes viral from the moment in which it accumulates a sufficiently strong critical mass to generate a self-sustained process of replication with geometric dispersion, such that, in the case of a chaotic system, the butterfly effect, itself, may be unstable, occurring a sudden acceleration in the dynamical sensitivity to disturbances.

The viral process just described is *autocatalytic* (Eigen and Winkler, 1985), in the sense that it is the system itself that generates the critical mass necessary for the viral explosion, which starts to feed from itself, that is, the viral dispersion virally feeds the viral dispersion. Internet worms constitute good examples of this dynamics, starting slow and quickly speeding up as a critical mass is attained, in terms of the number of infected systems, with an exponential growth phase, which slows down as the number of infected machines becomes saturated with fewer vulnerable machines left to infect[1]. The *Witty Worm*, however, following CAIDA's report[2], escaped this pattern, since it went into the viral growth phase within the first few seconds, infecting 110 machines in the first 10 seconds, which is considered to be highly improbable and so evidence of pretargeting either through a hitlist or through previously compromised vulnerable hosts used to start the worm.

The fast viral phase, however, is not the only statistical anomaly with the *Witty Worm*, if we order the number of infected hosts by country from the largest to the smallest, and plot it on a logarithmic scale with respect to the number of infected hosts (see Fig. 1 below) we obtain an almost straight line except for the first two countries, USA and UK, which show a significantly higher number of infections than the rest, which means that these two countries ended up being the main victims of the Worm (USA being the first location with the viral explosion).

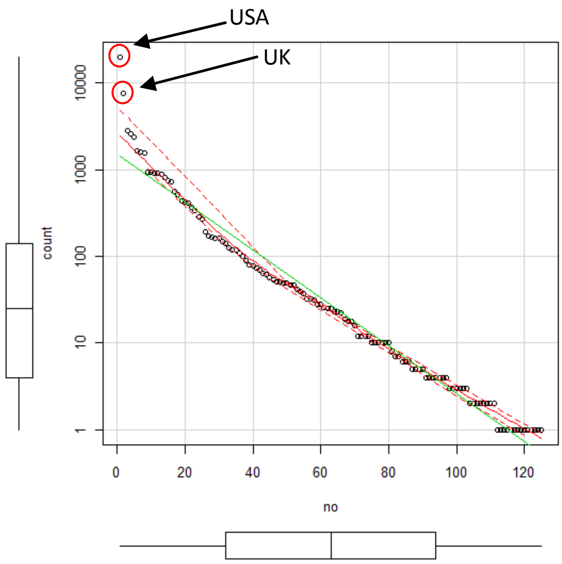

Fig. 1 – Country distribution of the number of infections. Source: CAIDA

The UK effect may be a network connectivity effect coming from the USA, while the USA infection pattern may explained from the fact that the the worm targets a

[1] This is well documented in the CAIDA report: http://www.caida.org/research/security/witty/.
[2] Report by Colleen Shannon and David Moore, hosted by CAIDA in the website: http://www.caida.org/research/security/witty/.

buffer overflow vulnerability in several Internet Security Systems (ISS) products, and US-based Internet Security Systems (ISS) companies' products were primarily affected but they do not possess a sufficiently high number of overseas operations[3].

The occurrence of viral dynamics, in the networks' evolutionary processes, can be generator of business opportunities, introducing a new dynamics of business cycle, with the possibility of sudden explosions in the business volume, but it can also be generator of systemic risk dynamics, with the possibility of occurrence of global crises with very rapid dispersion, leading to a high risk of systemic collapse (Ryan, 2009; Hayashi *et al.*, 2012).

4.2. Interconnected risk processes

The interconnectedness of risk situations demands of risk governance the application of network analysis tools that promote the identification of interconnected risk processes. The World Economic Forum has addressed this matter operatively through the *Risks Interconnection Map*, a visual tool that allows one to identify such processes.

In the 2012 version, the map is organized, from a survey to experts, in terms of five risk categories: economic, environmental, geopolitical, societal and technological (Hayashi, *et al.*, 2012). For each category there is a *center of gravity* with the major risk situations linked with it, a number of critical connectors, and a number of weak connections (representing weak signals). In this way the exposure to a specific risk situation implies the indirect exposure to all of the critical connectors for that situation, such that, for instance, one can be faced with a loss associated with a geopolitical domain coming from a technological domain.

Through the *Risks Interconnection Map*, one can see how experts are relating different risk sources. An example is the network that associates the *global governance failure* with cyberspace-related risks, the connectivity of the local network is shown in the following figure 2, drawn from the *Risks Report* (Hayashi, *et al.*, 2012, p.25)

[3] A factor that was pointed out in the previously mentioned CAIDA report.

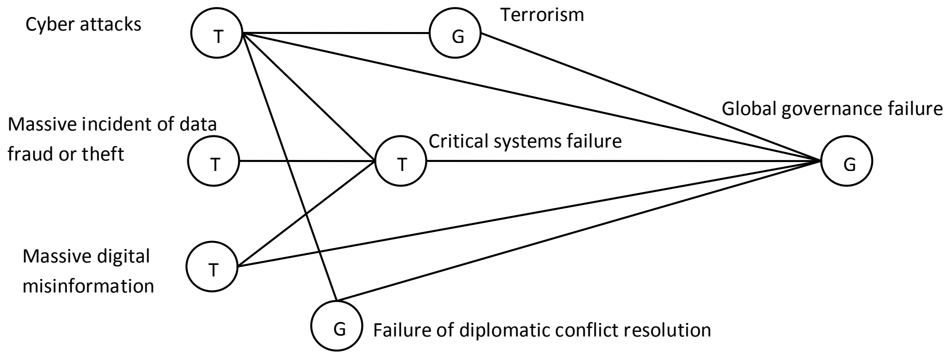

Fig. 2: *Risk Network* relating the cyber risk to the global governance failure. Only the connections and categories are shown (G = geopolitical, T = Technological). Source: World Economic Forum

The figure above shows only the connections, without any grading in terms of connection intensity. Considering only the connections, one already can extract relevant risk measurement procedures, by applying basic graph analysis tools.

Indeed, in a first analysis, one can consider, three numbers: (i) the number of nodes that are before *global governance failure*; (ii) the number of one-link neighbors of *global governance failure*, which constitute the most direct triggering factors of *global governance failure*, and (iii) the number of risk sources that reach the *global governance failure node* by more than one path. This provides for a triple characterizing the local risk network, in this case, one might count (6, 5, 4). The first number is the more straightforward to explain, there are six risk situation types in the network interconnected in paths to global governance failure.

Regarding the second number, the World Economic Forum has identified five risk sources with direct links to global governance failure: *terrorism; cyber attacks; critical systems failure; massive digital misinformation* and *failure of diplomatic conflict resolution*. Outside this list is the *massive incident of data fraud or theft* which has only an indirect connection to *global governance failure*. The five direct links, coming from the above five risk sources, can constitute direct sources of *global governance failure*, in particular if they take place simultaneously.

The third number in the triple depends upon the directions that one may assume in the connections, different experts may propose different directions for the connections and the result will be different. We are using the following:

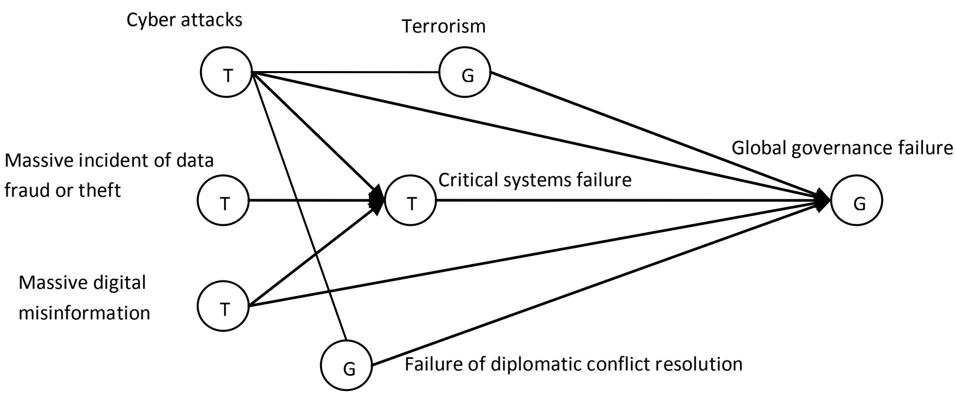

Fig. 3: Reviewed network with directions (the connectiom 'a -> b' means a may cause b, while simple connection 'a – b' means bidirectionality in causality (a can cause b and b can cause a)).

The third number tells us how many nodes are there that directly as well as indirectly affect *global governance failure*. Cyber attacks have more than one path to *global governance failure*, terrorism also, because, not only is it directly linked to *global governance failure*, but an increase in cyber terrorist activities may lead to cyber attacks which, in turn, are directly, as well as indirectly, linked to *global governance failure*. Failure in diplomatic conflict resolution can also lead to cyber attacks and, therefore, to governance failure (a local example was the attacks on Estonia (Davis, 2007)). All the nodes, except for massive incident of data fraud or theft and critical systems failure, have more than one path connecting them to global governance failure.

The multiple paths open up the possibility of multicausality and domino-like effects. For instance, failure in solving conflicts through diplomacy may deteriorate relations between countries, leading to threats to global governance (direct connection in the network), but this threat can be amplified if that failure leads to increasing cyber attacks that lead to critical systems failure and open the road for further increasing terrorist activities, in particular cyber terrorism.

The quotient between the number of nodes that are before *global governance failure* and the number of nodes that are linked by more than one path to *global governance failure* gives us a measure of multicausality (which is between zero and one), it can be interpreted as a probability measure, measuring the probability that a randomly occurring risk scenario may lead, through multiple paths, to *global governance failure*. In this case, the number is high 4/6, so one has approximately 66.7% probability of multicausality. One must take some care, in interpreting this probability measure, since it can only be interpreted as a conditional probability, conditional on risk scenarios in which the first event in the path triggers all of the subsequent events up to the threat to global governance being realized.

To complete the risk analysis one might enumerate a number of relevant combinations of paths, since each combination naturally leads to a different scenario. Thus, the network becomes a tool for systematic scenario generation.

Following the *global governance failure* risk network analysis example, one can generalize a ***methodology for interconnected risk situations' analysis***, in the form of the following four-step approach:

1. Draw the network of risk situations (with the causality links);
2. Calculate path-based risk measures;
3. Enumerate the paths and build scenarios from there;
4. Calculate probabilities and conditional probabilities for the different scenarios or simulate the risk scenarios in computer models that take into account the network structure.

In the fourth and last phase, one applies methodologies that are proper of the complexity sciences, in particular, game theory, quantum game theory, agent-based models and nonlinear network dynamics models and/or network stochastic process modeling to simulate and evaluate risk dynamics.

Regarding the modeling approaches, adaptive networks' dynamics show a specific systemic structure, since their dynamical processes are, for the most part, discrete in state, but showing dynamical expected values that can be modeled by continuous state processes (Gonçalves, 2012b). A great deal of relevant variables is, indeed, discrete, for instance: network traffic; the number of visualizations of a website, the number of people replicating a certain behavior pattern; the quantities of a given product sold; the shares of a company and the price of these shares.

To deal with these cases, quantum game theory and quantum econophysics, may provide for an important modeling tool for complex systems' modeling (Saptsin and Soloviev, 2009), since they allow one to combine adaptive behaviors with discrete state variables and continuous state dynamics (Gonçalves and Madeira, 2010; Gonçalves, 2012b). Furthermore, the quantum equations link directly the probability structure with the system's structure and dynamics, which is effective in risk modeling (Gonçalves, 2012a; 2012b).

There are already empirically testable applications of quantum games and quantum chaos to financial market modeling and to the modeling of competing networks of companies (Hanauske *et al.*, 2009; Gonçalves, 2012a; 2012b). Thus, quantum complexity sciences, a field in which the Brussels-Austin school has focused its work upon, combined with conceptual elements of risk science and the three main schools on complexity science, may supply conceptual solutions and effective mathematical tools to support risk governance in dealing with the modeling phase of interconnected risk/situations' analysis.

5. Conclusions

Organizations can no longer address risk from a local and reductionistic perspective, risk exposures must be addressed strategically and conjointly in their coevolving dynamics. The fact that the human civilization has become interconnected on a planetary level has led to an interconnectivity between risk situations, so that risk exposures depend upon a complex web in which different domains appear interconnected: economic and financial, environmental, geopolitical, societal and technological.

Within such a setting, *risk management* must be addressed at a key strategic level within organizations, which must develop a risk governance structure responsible for risk management, which must guarantee that mechanisms and procedures are in place for strategic risk planning, integrated risk analysis and risk monitoring procedures.

The main result of the present work is a general approach to the development of risk governance decision support systems, based upon risk science and the complexity sciences. It is this approach that we now synthesize, as a main conclusion, in connection with the work developed above.

One can address risk management processes in terms of an RCM (*Risk Consequence Measurement*) approach. The *R* stage of RCM involves the identification of risk sources and the linkages between these sources. As was addressed in the present work, at this level, one can apply the tools of interconnected risk situations' analysis which include drawing the network of risk situations with respective causality links. At this stage, the application of methodologies from risk science and risk mathematics may be useful in synthesizing an initial general scenario analysis underlying the risk network structure, applying the graph analysis tools, one can build a preliminary network-based risk evaluation report quantifying a risk exposure associated with the interconnectivity of the network.

The consequence stage (stage *C*) of the RCM approach involves the evaluation of loss distributions, associated with different risk scenarios. At this stage, the application of the tools of interconnected risk situations' analysis may be useful to produce scenarios from the risk network, and to address possible measures. At the end of this stage, plans regarding measures to be taken for adverse scenarios should be produced with consequences for the organizations' management.

The third stage (stage *M*) involves calculating probabilities and conditional probabilities, which can be addressed from the risk network structure. In this case, dynamical probabilities and adaptive agent-based modeling may be employed to address the possibility of changing risk dynamics. Quantum game theory can be useful, since it allows one to obtain equations for probability structures and dynamics directly from the assumptions regarding the system's decisional structures and network of relations, from where one obtains not only a family of probability measures but also an appropriate dynamics for probability dynamics (changing or coevolving probability structures).

In this way, risk measurement, risk dynamics' analysis and action plans can be built towards an integrated risk planning at the risk governance level of analysis. Future academic work in this area may also be applied with decisional consequences in risk science research, that is, the methodology proposed here is also adaptable to academic research.

Bibliography

Ball, P. (2004), Critical Mass – How One Thing Leads to Another, USA, Farrar, Straus and Giroux.

Barabási, A.-L. and Bonabeau, E., "Scale-Free Networks", Sci. Am., May, 50-59.

Beck, U. [1992], (2000), Risk Society – Towards a New Modernity, Translated by Mark Ritter, UK, Sage.

Boldrin, M. and Woodford, M., "Equilibrium Models Displaying Endogenous Fluctuations and Chaos: A Survey", in Benhabib, J. (org.), (1992), Cycles and Chaos in Economic Equilibrium, USA, Princeton University Press, pp.8-43.

Bollier, D. (2009), Viral Spiral: How the Commoners Built a Digital Republic of Their Own, USA, New Press.

Bradley, E. and Mantilla, R. (2002), "Recurrence Plots and Unstable Periodic Orbits", Chaos 12, pp. 596-600.

Bremmer, I. and Keat, P. (2010), The Fat Tail: The Power of Political Knowledge in an Uncertain World, USA, Oxford University Press.

Davis, J. (2007), "Hackers Take Down the Most Wired Country in Europe", Wired, Issue 15.09, (http://www.wired.com/politics/security/magazine/15-09/ff_estonia?currentPage=all)

Doherty, N., “Climate Change, Insuring Risk and Changes in Risk”, *in* Michel-Kerjan, E. and Slovic, P. (Eds.), (2010), The Irrational Economist, USA, PublicAffairs.

Ebel, H., Mielsch, L.-I., Bornholdt, S., (2002), “Scale-free topology of e-mail networks”, Phys. Rev. E 66 (2002) 035103(R)

Eigen, M. and Winkler, R. (1985), “Das Spiel. Naturgesetze Steuern den Zufall”, Alemanha, Piper, Verlag.

Easley, D., Marcos, M.L. and O’Hara, M. (2011), “The Microstructure of the “Flash Crash”: Flow Toxicity, Liquidity Crashes, and the Probability of Informed Trading”, The Journal of Portfolio Management, Winter, Vol. 37, No. 2, pp. 118-128.

Guilhou, X. and Lagadec, P. (2002), La fin du risque zero, France, Eyrolles Editeur.

Gleick, J. (2011), The Information: A History, A Theory, A Flood, USA, Pantheon.

Gonçalves, C.P. and Madeira, M.O. (2010), Chaos Artificial Life and Risk Mathematics, Microeconomics: Decision-Making under Risk & Uncertainty eJournal, Vol. 1, Issue 119, (2010).

Gonçalves, (2012a), “Financial Turbulence, Business Cycles and Intrinsic Time in an Artificial Economy”, Algorithmic Finance, Forthcoming.

Gonçalves, (2012b), “Chaos and Nonlinear Dynamics in a Quantum Artificial Economy”, arXiv:1202.6647v1 [nlin.CD].

Hakken, H. (1977), Synergetics: An Introduction, Alemanha, Springer.

Hanauske, M., Kunz, J., Bernius, S. and König, W. (2009), “Doves and hawks in economics revisited: An evolutionary quantum game theory based analysis of financial crises”, Physica A, Vol.389, Issue 1, pp. 5084-5102.

Hayashi, Chiemi; Gleicher, David; Ramseger, Florian; Campbell, Karen; Soo, Amey; Tonkin, Samantha; Wright, Andrew and Stefaner, Moritz (2012), Global Risks 2012 – Seventh Edition, Suíça, World Economic Forum.

Helbing, Dirk (2009), "Systemic Risks in Society and Economics", Paper #: 09-12-044, Santa Fe Institute Working Paper Series.

Holland, J.H. (1995), Hidden Order – How Adaptation Builds Complexity, Helix Books, USA.

Holland, J.H. (1998), Emergence, From Chaos to Order, Perseus Books, USA.

Kaneko, K. and Tsuda, I. (2001), Complex Systems: Chaos and Beyond, A Constructive Approach with Applications in Life Sciences, Alemanha, Springer.

Lewin, R. (2000), Complexity. Life at the edge of chaos, USA, University of Chicago Press.

Lorenz, E. W. (1995), The Essence of Chaos, USA, University of Washington Press.

Morin, E. (1998), Sociologie: édition revue et augmentée par l'auteur, France, Libraire Arthème Fayard.

Peitgen, H.-O.; Jürgens, H. and Saupe, D. (2004), Chaos and Fractals, New Frontiers of Science, USA, Springer.

Prigogine, I. (1962), Introduction to Thermodynamics of Irreversible Processes, USA, John Wiley and Sons.

Prigogine, I. and Stengers, I. (1986), La nouvelle alliance, France, Éditions Gallimard.

Prigogine, I. (2001), La fin des certitudes, France, Odile Jacob.

Püu, T. (1997), Nonlinear Economic Dynamics, Germany, Springer-Verlag.

Ryan, F. (2009), Virolution: The most importante evolutionary book since Dawkin's Selfish Gene, Reino Unido, Collins.

Saptsin, V. and Soloviev, V. (2009), "Relativistic quantum econophysics - new paradigms in complex systems modeling", arXiv:0907.1142v1 [physics.soc-ph].

Stacey, R. D. (1992), Managing Chaos, USA, Kogan Page Limited.

Stacey, R.D. (1995), The Chaos Frontier, USA, ButterWorth-Heinemann.

Taylor, C. (2012), "As consumer power goes viral, company branding quakes", Reuters, http://www.reuters.com/article/2012/01/06/us-usa-companies-backlash-idUSTRE80424T20120106.

Varela, F. (1997), Invitation aux sciences cognitives, 1997, France, Seuil.

Whitfield, J. (2008), "Risk in Financial Markets – Learning from Nature", Santa Fe Bulletin, Vol.23, 1, Spring, 33-37.