NEST

GIACS

General Integration of the Applications of Complexity in Science

Coordination action

Italian National Agency for New Technologies, Energy and the Environment

D3 - Complexity in Human and Infrastructures networks

Start date of project: July 15th 2005 Duration:36 month

Data of issue: July 20th 2006

Summary Report on STREP's activity on Large Complex Critical Infrastructures (LCCI)

WP3: the ENEA Working Group
V.Rosato, L.Issacharoff, S.Bologna
ENEA, Casaccia Research Center, Roma (Italy)

July 20, 2006

Abstract

This document reports a brief state–of–the–art on the application of the ideas and methods of *Complex Systems* to investigate structural and functional properties of Large Complex Critical Infrastructures (LCCI). The analysis is performed in order to predict possible uses of NEST STREPs results in this context and to envisage future collaborations between the Complex Sciences community and the LCCI owners and stake-holders.

1 Introduction and motivation

This document is part of the activity performed in the GIACS Support Action aimed at finding specific issues and methods of Complex Sciences which might be of some help in solving technological problems related to the `intrinsic vulnerability` affecting Large Complex Critical Infrastructures (LCCI).

LCCI are the technological networks (electrical power transmission, communication, traffic networks, oil and gas supply etc.) whose malfunctioning or faults have a large impact on society. LCCI are complex systems: as such, they can be analyzed under the standpoint of Complexity Science in order to understand their behavior and possibly to predict the onset of *emergent* properties, whose occurrence is typical of Complex Systems. LCCI are, moreover, *interacting* complex systems: they could also present emergent behaviors very difficult to be predicted, related to their mutual interdependency.

In this respect, the use of instruments, methods and *ideas* from the Complexity Sciences could result in some benefit for helping LCCI stakeholders in analyzing and monitoring their systems. New tools could be designed and realized to help them in designing, analyzing, controlling and managing such complex systems, particularly under the form of Decision Support Systems (DSS). These tools could be realized by fostering a collaboration between the scientific community and the LCCI stakeholders. The WP3 of project GIACS intends to accomplish this task.

2 Hierarchy of LCCI and major concerns

Until recently, technological infrastructures have been seen (mostly) as non–interacting systems; as such, they have been operated, studied, and analyzed *independently*, usually with *ad hoc* engineering tools developed for specific purposes (such as VISUM for transportation planning [1]).

During the past decade, the large outages experienced by LCCIs (like, e.g. the Italian and US blackouts on 2003) on one side, and the efforts produced in the field of complex systems science on the other, have provided a new outlook on the common properties of these systems and on their interdependence, as well as the needs of realizing some unified framework for analyzing their properties.

Such a framework is based on the idea that critical infrastructures are, in general, large networks over which a transportation process occurs (electricity, water or vehicles). In this sense, LCCIs may be firstly described, at the lowest level, as `graphs`, with *nodes* representing the entrance, passage or exit points of the transportation flow and with *edges* representing the "pipes" or the "roads" along which the flow runs. Evaluating the reliability or the vulnerability of different LCCIs ultimately means understanding the properties of the flow on different network architectures and assessing the effect of the network's structure in determining that behavior.

Once this setup is established, it is clear that evaluating the reliability of LCCIs requires an approach on, at least, two levels. On one hand, one has to consider the underlying network, and specifically its topological properties and its evolution (which may take place through the addition or the deletion of links and nodes). General studies of complex systems classify networks according to their topology [2, 3] and identify common topological characteristics with which a vulnerability assessment is possible [4]. Topological properties are also important to evaluate the resiliency of networks to deliberate attacks [5, 6]. On the other hand, one has to study the transportation process on a given network, which is relevant for understanding failure spreading. Different dynamics of propagation in networks are, for instance, used to study cascading effects on networks [7]. These two sides are not separated, as topological properties influence dynamical properties and optimal dynamical properties can be achieved by changing the network structure.

Both levels can be tackled effectively by computer analysis, either for real data statistics (which is crucial for retrieving the topological and growth properties of the physical networks) or for simulating the transport process. Similarly, one may be interested in comparing the real flow with the optimal flow that a network allows, for which purposes specific optimization algorithms are used. More theoretical approaches, based on diffusion equations and non-equilibrium statistical mechanics, may be important when dealing with some specific aspects of the transport dynamics.

More specific approaches and issues for each type of the infrastructures are reported in the following section where we report some recent results obtained by the Complex Sciences community which might be of interest for the LCCI stakeholders and which can contribute to bridge the gap between scientific results and real–case applications needed by LCCI stakeholders.

2.1 Electrical networks

The interest of the complexity science community in the electric power systems has been boosted by some major blackout events such as the North American power grid blackout of August 2003 and the Italian blackout of September 2003.

Applications of complexity science to electric power systems are being carried out along two main lines, namely through a topological approach and a dynamical one. The aim is that of revealing the main characteristics of the power grids and the mechanisms behind the cascading failure effects causing blackouts. A higher understanding of topological and dynamical properties could be used for decreasing the electrical power networks vulnerability by better planning of future systems, improvement of current ones and decreasing the probability of the occurrence of major failures in the future.

The first studies have been carried out on the networks' topology. Different electrical grids of high voltage transmission lines were examined. For example, in [8, 9] the topological analysis of the North American and Italian grids have been performed. These analysis include the calculation of different global quantities such as the nodes' degree distribution, several *centrality* properties (betweenness, information, load etc.); moreover they have attempted to estimate which components of the network are more liable to cause the biggest damage in case of malfunctioning. In particular, Ref. [8] shows that it is the transmission hubs, and not the generation hubs, that are more likely to cause power breakdowns. The spectral analysis performed in [10] shows instead which are the "weakest links" of the Italian grid. In [11] the Barabási-Albert network model is used to evaluate the North American electric grid reliability. These applications showed that knowledge of the networks topology is important for assessing its vulnerability.

On the dynamical side, some applications of complexity science to power systems describe the cascading events causing blackouts as a self-organized critical phenomenon similar to those observed in other physical systems [12]. An example is the work of Ref. [13], that uses the 73 bus IEEE reliability test system to model the complex dynamics in electric power systems blackouts. This model describes quantitatively the opposing forces which have been conjectured to cause self-organized criticality in power system blackouts and shows that their balance results in a dynamical equilibrium in which blackouts of all sizes occur.

In a more recent activity [14], methods of graph's spectral analysis have allowed to highlight the set of transmission lines which could be used to produce a successive "islanding" of a complex electrical transmission network (the case study was the Italian grid). The same study has also put in evidence the lines of high vulnerability (those whose removal more sensibly reduces the capacity of the network to transport electrical power).

2.2 Communication network: the Internet and the World Wide Web

Since the seminal work of Ref. [15], there has been growing interest on the World Wide Web and the Internet seen as complex networks. At odds with most of the other LCCIs, data concerning the internet and the world wide web are abundant and easy to obtain. This fact, and, indeed, the growing importance of the internet as a tool with a higher and higher impact on society, have made this network an attractive research subject. Various topological analysis have been performed using different methods such as graph theory, spectral analysis [16] or k-shell analysis [18]. An additional difference between the Internet and other LCCIs is the time scale over which topology changes occur: such a time scale is typically very short for the Internet and the World Wide Web. Many studies have examined this aspect and several growth mechanisms were suggested, as in Ref. [20]. These models were then used as a basis for the analysis of the dynamical process running on the network such as package distribution, round-trip-time [21] and search mechanism [17]. Another class of models concerning the network's performance examines instead such phenomena as congestion [22, 23] Other studies have focused on the reliability and vulnerability of the network [20]. Finally, vulnerability to virus spreading has also been analyzed, mainly through analogies with epidemic contagion in population dynamics models. An extensive review of the applications of complexity science to the internet network is introduced in Ref. [19]

2.3 Traffic network: roads and railways

Traffic flow models have been a major study subjects of physicists since the early nineties and extensive reviews are present in the literature [24, 25]. Most of these works are aimed at understanding some peculiarities of traffic flow, such as stop-and-go regimes and traffic jams. The infrastructures where traffic flow occur are usually taken as given; only recently a little attention has been devoted to the study of the topological properties of the road networks of major German cities [26] and of the Indian railway network [27]. This fact is in a great part due to the difficulty in acquiring data. It would be important to address the issues of vulnerability and reliability in traffic networks similarly to what is done for electric power systems. This field is of major relevance in countries where the road traffic is intense and there are several national plans to shift a larger and larger part on it on rails. It is thus expected a common frame able to allow the implementation on a joint road-rail integrated system, supply chain simulations and optimizations.

3 Connection with GIACS/STREPS

A preliminary analysis of the GIACS' STREPS [28] has shown that there is a very weak link between outcome of such projects and the needs for LCCI reliability and vulnerability analysis. Its main reason reside in the gap between LCCIs stakeholders and the community of the Complexity Science. In spite of all the different attempts to fill in this gap in the last few years the results have been very unsatisfactory for the following two reasons:

- LCCIs stakeholders do not understand the physical meaning of the results coming from the application of the complexity science methods and ideas;
- scientists do not seem to care about applying their tools and methods on real systems (whose data are not always available to the scientific community).

This was proved also from the preliminary attempts to apply GIACS' STREPS results to real LCCIs.

4 ENEA ongoing activities: models and methods

Following the very poor results coming from the attempt to use GIACS' STREPS, ENEA is going to produce, by its own, in the frame of several national and EU–funded projects, a considerable effort in the direction of bridging the gap between LCCI and basic science. The major concern is related to the definition of dynamical models of LCCIs able to treat the interdependence–related phenomena. ENEA is currently developing dynamical models of the following LCCI: high–voltage power transmission networks, the communication network managed by the TCP/IP protocol, the urban and extra–urban vehicular traffic and the railways. The ambitious goal is to realize "joint" simulations of all the LCCI couples, in order to identify and to possibly estimate the "interdependence degree" between these systems [29].

ENEA has recently realized a dynamical model of the Internet, by using structural data of the world–wide Internet map provided by the EU–funded project DIMES [30]. This could be used as a test–bed to evaluate the behavior of regional subnetworks, under normal and abnormal (i.e. upon faults) behavior [31, 32].

At the same time, ENEA has realized a simple DC–power flow model representing the electrical flux into the Italian high–voltage (380 kV) transmission network. This has been used to put in evidence the vulnerability of the network, on both the topological and the dynamical standpoints [10, 14].

5 ENEA proposal

Once the forum of Complexity Scientific Research Project, Torino 27-28 July, 2006, will have verified the correctness of our analysis of GIACS-STREPS, ENEA intends to call for a workshop on the subject of "Complexity Science and LCCIs". The call will be restrained to an invited set of scientists, coming both from LCCI stakeholders and from academia, with experience in applying Complexity Science to LCCI. Previous to the Workshop a collection of the most relevant papers published on the recent years about the applications of the complexity science methods and techniques to technological LCCIs will be made available on the GIACS website to all the potential interested LCCIs owners/operators. If none of the GIACS-STREPS may contribute to the Workshop, the speakers will be invited among the authors of the most relevant papers mentioned above.

References

[1] http://www.ptvamerica.com/visum.html

[2] R Albert and AL Barabasi, Rev. Mod. Phys. **74** 47 (2002)

[3] M Newman, AL Barabasi and DJ Watts, *The Structure and Dynamics of Networks* (Princeton University Press)

[4] V Latora and M Marchiori, Phys. Rev. E **71** 015103(R) (2005)

[5] L Zhao *et al.*, Phys. Rev. E **72** 025104(R) (2005)

[6] L Gallos *et al.*, Phys. Rev. Lett. **94** 188701 (2005)

[7] A Motter and Y-C Lai, Phys. Rev. E **66** 065102(R) (2002)

[8] R Albert *et al.*, Phys. Rev. E **69** 025103(R) (2004)

[9] P Crucitti *et al.*, Physica A **338** 92 (2004)

[10] V.Rosato *et al.*, Electr.Pow.Syst.Res. (2006) in press.

[11] D P Chassin C Posse, Physica A, **355**, 667-677 (2005)

[12] HJ Jensen, *Self-Organized Criticality : Emergent Complex Behavior in Physical and Biological Systems* (Cambridge University Press)

[13] B A Carreras *et al.*, Proc. 34th Hawaii Conf. System Sciences (2001)

[14] V. Rosato, L.Issacharoff, S.Bologna, submitted to Phys. Rev. E

[15] M Faloutsos *et al.*, Proc. Conf. ACM-SIGCOMM (1999)

[16] D Vukadinovic' *et al.*, ETH TIK-NR. 118, JULY 2001

[17] S Carmi R Cohen D Dolev, Europhys. Lett, **74** (6), pp. 1102-1108 (2006)

[18] S.N. Dorogovtsev,A.V. Goltsev, J.F. Mendes Phys. Rev. Lett. 96, 040601 (2006)

[19] R Pastor-Satorras and A Vespignani, *Evolution and Structure of the Internet: A Statistical Physics Approach* (Cambridge University Press)

[20] V Rosato and F Tiriticco, Europhys. Lett. **66** 471 (2004)

[21] R Percacci and A Vespignani, Eur. Phys. J. B **32** 411 (2003)

[22] D J Ashton, T C Jarrett, N F. Johnson, Phys Rev Lett 94, 058701 (2005)

[23] J Steger, P Vaderna, G Vattay, Phys. A, **359** 784-792 (2006)

[24] D Helbing, Rev. Mod. Phys. **73** 1067 (2001)

[25] D Chowdhury *et al.*, Physics Reports **329** 199 (2000)

[26] S Lämmer, B Gehlsen, D Helbing, Physica A 363(1) 89-95 (2006)

[27] P Sen *et al.*, Phys. Rev. E **67** 036106 (2003)

[28] ENEA six month report (2006)

[29] L Issacharoff *et al.*, Proceedings of the Conference "Complex Networks and Infrastructure Protection" (CNIP 2006), Roma March 28-29, 2006.

[30] see the web page of the project `www.netdimes.org`.

[31] F. Tiriticco, Thesis of II Level degree in Telecommunication Engineering, University of Roma "Tor Vergata" (2006). Copy of the Thesis can be obtained at the e-mail: `tirix3@libero.it`.

[32] V.Rosato *et al.*, in preparation (2006)