Università Campus Bio-Medico di Roma
School of Engineering
PhD Course in Biomedical Engineering

(XXI - 2006/2008)

Complex Systems: analysis methods

Stefano De Porcellinis

Complex Systems: analysis methods

A thesis presented by
Stefano De Porcellinis
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
in Biomedical Engineering
Università Campus BioMedico
di Roma
School of Engineering

Coordinator:

Prof. Saverio Cristina

Supervisor:

Prof: Roberto Setola

February 2009

Stefano De Porcellinis

Contents

Introduction

The word "complex" is always associated, in our mind, to something obscure, hard to explore and difficult to handle. Such a negative acceptation, often, is confused in the common sense with the word "complicated". In systems theory instead, while "complicated" deals with the limits of our capabilities to understand a given phenomenon, "complex" completely takes on a different meaning. Here complexity deals with intrinsic properties and characteristics of the systems. Complex systems shows peculiarities and behaviours which are difficult to understand or seem to unpredictable because, within it, there exist many mechanisms and interactions that make emerge properties that do not belong to any element in the system. According to such observation, "complexity" does not represent the result of the limit of our reason, but the effect of a "complicated" structure, the dynamics lying over such a structure and the mechanisms which drive its forming.
Complex systems, according to the previous defintion, appear in many different contexts, from biology to sociology and technological platforms, but, in spite of the context differences, their handling requires to face-off with common issues. The investigation on complex systems, indeed, always leads to clash with a common set of challenges, which can be summarized in the phrase "The result is not the sum of parts". Complex systems always perform behaviours which are not deducible by a spot observation of their components, their analisys has to take into account their history, the paths followed by the elements to form the systems, the interaction among such elements

and the influence of the environment in which the systems live. Such a kind of knowledge is never easy to acquire and also when acquired, it could result only in a partial view of the full picture, strictly related with the unconscious assumptions made during the investigation process. When we proceed with our analyses, which always requires a sort of "in-vitro" reproduction of the investigated system. It is mandatory to rembember that the (always necessary) restrictions and hypotesis undertaken influence the results achieved. In the following I will show the methods and the techinques that have been developed during my experience as Doctoral student in the University "Campus Bio-medico di Roma" and the innovative results obtained with help of my tutor and of many colleagues from national and international research centres. The First chapter will outline the reference context and will provide some notations and hystory about the complex system theory. The Second chapter will deal with topological models and structural issues of technological systems. The Third and Fourth chapter will tackle the two opposite perspectives which can be undertaken in order to implement dynamical models of complex systems, specifically, an "holistic" perspective and a simulation driven approach. The last chapter will present an innovative multi-scale modeling methodology, which can exploit the advantages of the previous methdologies, overcoming some of the limits shown by single scale approaches.

Chapter 1

Reference context

1.1 Common features and uncommon behaviours

Complex systems, according to the previous definitions, often show a set of common "unsual behaviours" and, in spite of the differences that exist among systems in different domains can always be reconducted to a sort of anarchic existence. When we observe how such systems react when solicited by perburbations, we always observe some common features in their response: they are highly nonlinear and often show chaotic behaviours.

Another feature which repeatedly frustrates our insights is the existence, inside many of these systems, of some unwritten treaties among the elements which, under particular conditions, coordinate themselves to let emerge completely unpredictable and different behaviours. Such a kind of phenomena, known in physics with the name of "percolation", is observable in many natural, sociological and technological systems. There are no apparently reasonable causes to explain, for example, that in given moment, the diffusion of a circumscribed epidemic turns out into a pandemic, or for the transition in a telecommunication network, from high traffic condition into a locking saturation of the bandwidth.

So, how should we have to pursue the Chimeric illusion to understand such elusive systems, which try to disrupt all our convictions about the commonly sensed existence of cause-effect relationships in the nature?

Probably the same "common" anarchic nature of those systems may suggest us how to face it.

The observation of these so common and diffused "uncommon" behaviours may suggest us the existence of an hidden relationship among those systems, among their nature, their structures and the way their elements interact each others. It could be possible (in reality we are strongly convinced about that) that, focusing our attention on the common phenomena which drive the dynamics of complex systems, we could develop theoretical and practical tools able to break the smokescreen that still obscures our comprehension about complexity.

1.2 Topological issues

When dealing with systems and their structure, a first analysis should be obviously directed to their topology. Indeed, analysing the graph underliyng the interactions among the elements, it is possible to deduce several structural properties of system: invariants, clusters and the most important nodes with respect to the topology.
Many indicators can be extracted from a plain topological assessment of a system, let's cyte the most common.

Given the graph G, defined as the set of nodes $V = x_0, x_1, ..., x_n$ and edges $E = e_0, e_1..., e_m$, we could define:

- Degree of a node v, $d(v)$, as the the number of edges that are adjacent to the node;

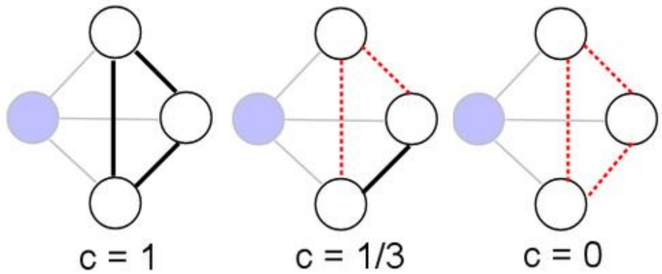
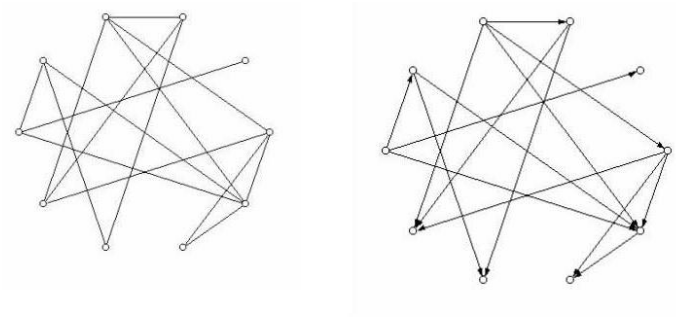


Figure 1.1: Clustering coefficent for a node.

- Average degree of a graph G, $d(g) = \frac{1}{|V|}\sum_{v \in V} d(v)$;
- Path is the non-empty graph $P = (V, E)$ of the form $V = \{x_0, x_1, ..., x_k\}$ $E = \{x_0x_1, x_1x_2, ..., x_{k-1}x_k\}$, where x_i are all distinct;
- Distance among two nodes x and y, $d_G(x, y)$, is defined as the lenght of the shortes $x - y$ path in G;
- Diameter of G, as the greatest distance $d_G(x, y)$ between any two vertices x and y in G;
- Neighbourhood N_i for a node x_i, as its immediately connected neighbours, $N_i = \{x_i : e_{ij} \in E \vee e_{ji} \in E\}$;
- Clustering coefficent C_i for a node x_i, as the proportion of edges between nodes within its neighbourhood divided by the number of links that could possibly exist between them, $C_i = \frac{|\{e_{jk}\}|}{d(x_i)(d(x_i)-1)} : x_j, x_k \in N_i, e_{jk} \in E$ (See Figure 1.1);
- Clustering coefficent for the whole system $\overline{C}$, as the average of the clustering coefficent for each vertex, $\overline{C} = \frac{1}{n}\sum_{i=1}^{n} C_i$.

Up to 20th years ago, the graph theory developed to explore complex systems properties, was based on the random graph theory developed by



(a) (b)

Figure 1.2: (a) Random graph. (b) Directed random graph.

famous Mathematician Paul Erdős (1913-1996). According to such theories, the simplest way to create a network is to play a dice: hoose two nodes and, if you roll six, place a link between them. For any other roll of the dice, do not connect the two nodes but choose a different pair and start over. Therefore, according to the theory of Erdős, graphs and the world they represent were fundamentally random. Such a kind of assumption could seem to be reasonable, especially in a complex world where the laws that underlie the creation of links among nodes are not recognizable. When analysing random graphs, it is possble to discover that all the nodes are caracterized by a similar *degree* and then, the distribution of these degrees is a gaussian.

Even if the Erdős theory was fascinating, especially for the simplicity with which it permitted to explore the properties of very large systems, sometimes it appears to clash with some practical experiences. According to a completely random topology, the mean distance among the nodes has to proportionally grow with the number of the nodes. This characteristic, instead, is not found in many real systems (let's think, for example, to the extimated 6 degrees of separation, based on reciprocal knoweldge, among the people in the world) [A.L. Barabási, 2001].

1.2.1 Small-world systems

In the late 1960s, Stanley Milgram performed the famous small-worlds experiment. While no physical networks were constructed during the experiments, the results provided valuable insights into the structure of social networks. Essentially, the experiment examined the distribution of paths lengths in an acquaintance network by asking participants to pass a letter to one of their first-name acquaintances in an attempt to get the letter to the designated target. While most of the letters were lost, about one quarter reached the target person. On the average, such letters passed through the hands of 5/6 people. This experiment was the source of the popular concept of 6 degrees of separation.

The ground breaking work of Watts and Strogatz [D.J. Watts, S.H. Strogartz, 1998] showed that many complex networks display two key features: they possessed the 6 degrees of separation phenomenon, that Milgram discovered; but locally they had many properties similar to that of a regular lattice. In an attempt to model these systems Watts and Strogatz [D.J. Watts, S.H. Strogartz, 1998, D. Watts, S. Strogartz, 1999] proposed a one-parameter model, which interpolates between an ordered finite dimensional lattice and a random graph. The algorithm behind the model is as follows: start with a regular ring lattice with equation nodes in which every node is connected to its first equation neighbours (equation neighbours on either side); and then randomly rewire each edge of the lattice with a probability equation such that self-connections and duplicate edges are excluded. This process introduces long-range edges which connect nodes that otherwise would be part of different neighbourhoods (named "Short-Cuts"). Varying the value of the probability threshold moves the system from being fully ordered to a random one. Figure 1.3 shows some steps of this transition.

Purely random graphs, built according to the ErdősRényi model, exhibit a small average shortest path length (varying typically as the logarithm of the number of nodes) along with a small clustering coefficient. On the other side,

Stefano De Porcellinis

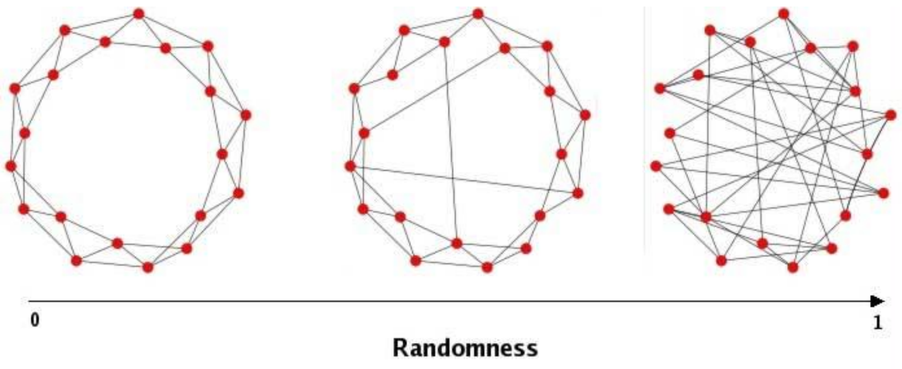


Figure 1.3: Progressive transition between regular and random graphs

a lattice network is characterised by a large shortest-path length and a large clustering coefficient. Watts and Strogatz measured that many real-world networks have a small average shortest path length, but also a clustering coefficient significantly higher than the expected by random model. Watts and Strogatz then proposed a novel graph model, now currently named the *small world* model, which allows (i) a small average shortest path length, and (ii) a large clustering coefficient. The first description of the crossover in the Watts-Strogatz model between a "large world" (such as a lattice) and a small-world was described by Barthelemy and Amaral in 1999. This work was followed by a large number of studies including exact results [Barrat and Weigt, 1999].

By virtue of the above definition, small-world networks will inevitably have high representation of cliques, and subgraphs that are few edges shy of being cliques, i.e. small-world networks will have sub-networks that are characterized by the presence of connections between almost any two nodes within them. This follows from the requirement of a high cluster coefficient. Secondly, most pairs of nodes will be connected by at least one short path. This follows from the requirement that the mean-shortest path length be small.

Small-world networks have been discovered in a surprising high number of natural phenomena. For example, networks composed of proteins with connections indicating that the proteins physically interact have power-law obeying degree distributions and are small-world. Similarly transcriptional networks in which genes correspond to nodes, and up or down-regulatory genetic influence correspond to connections are small world networks obeying power-laws.

There are also many other graphs which have been found to exhibit small-world properties. Examples include road maps, food chains, electric power grids, metabolite processing networks, neural networks, voter networks, telephone call graphs, and social influence networks.

1.3 Power law and scale-free systems

Studying the networks of citations between scientific papers, Derek de Solla Price showed in 1965 that the number of links to papers (i.e., the number of citations they receive) had a heavy-tailed distribution following a Pareto distribution or power law, and thus that the citations network was scale-free. He did not however use the term "scale-free network" (which was not coined until some decades later). In a later paper in 1976, Price also proposed a mechanism to explain the occurrence of power laws in citation networks, which he called "cumulative advantage" but which is today more commonly known under the name of "preferential attachment".

Recent interest in scale-free networks started in 1999 with work by Albert-László Barabási and colleagues at the University of Notre Dame who mapped the topology of a portion of the Web [Barabási, 1999], finding that some nodes, which they called "hubs", had many more connections than others and that the network as a whole had a power-law distribution of node's degree.

After finding that a few other networks, including some social and bi-

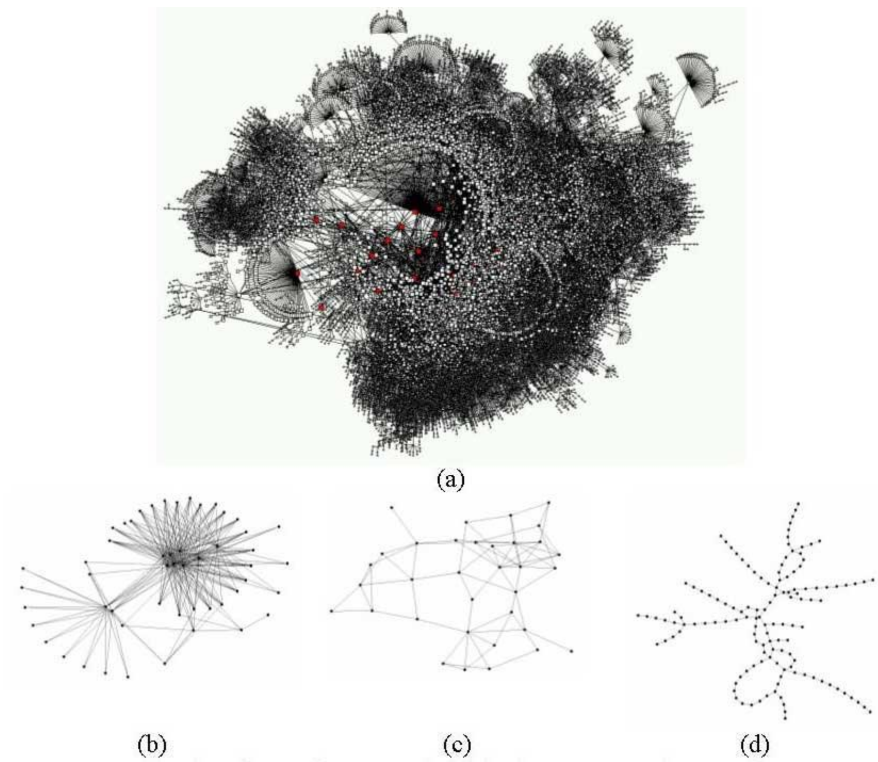


Figure 1.4: (a) the Internet, where nodes are routers and edges show physical network connections. (b) an ecosystem (c) professional collaboration networks between doctors; and (d) rail network of Barcelona, where nodes are subway stations and edges represent rail connections.

ological networks, also had heavy-tailed degree distributions, Barabsi and collaborators coined the term "scale-free network" to describe the class of networks that exhibit a power-law degree distribution. Soon after, Amaral et al. showed that most of the real-world networks can be classified into two large categories according to the decay of $P(k)$ for large k.

Barabási proposed a mechanism to explain the appearance of the power-law distribution, which they called "preferential attachment" and which is essentially the same as that proposed by Price. Analytic solutions for this mechanism (also similar to the solution of Price) were presented in 2000 by Dorogovtsev, Mendes and Samukhin and independently by Krapivsky, Redner, and Leyvraz, and later rigorously proved by mathematician Bla Bollobs. Notably, however, this mechanism only produces a specific subset of networks in the scale-free class, and many alternative mechanisms have been discovered since.

1.3.1 Characteristics of scale-free networks

As with all systems characterized by a power law distribution, the most notable characteristic in a scale-free network is the relative commonness of vertices with a degree that greatly exceeds the average. The highest-degree nodes are often called "hubs", and are thought to serve specific purposes in their networks, although this depends greatly on the domain.

The power law distribution highly influences the network topology. It turns out that the major hubs are closely followed by smaller ones. These ones, in turn, are followed by other nodes with an even smaller degree and so on. This hierarchy allows for a fault tolerant behavior. Since failures occur at random and the vast majority of nodes are those with small degree, the likelihood that a hub would be affected is almost negligible. Even if such event occurs, the network will not lose its connectedness, which is guaranteed by the remaining hubs. On the other hand, if we choose a few major hubs and take them out of the network, it simply falls apart and is turned into a set of rather isolated graphs. Thus hubs are both the strength of scale-free networks and their Achilles' heel.

Another important characteristic of scale-free networks is the clustering coefficient distribution, which decreases as the node degree increases. This distribution also follows a power law. This means that the low-degree nodes belong to very dense sub-graphs and those sub-graphs are connected to each other through hubs. Consider a social network in which nodes are people and links are acquaintance relationships between people. It is easy to see that people tend to form communities, i.e., small groups in which everyone knows everyone (one can think of such community as a complete graph). In addition, the members of a community also have a few acquaintance relationships to people outside the community. Some people, however, are so related to other people (e.g., celebrities, politicians) that they are connected to a large number of communities. Those people may be considered the hubs responsible for the small world phenomenon.

The mechanism which lead the aggregation of nodes around the most *connective* elements in the network is often called *preferential attachment*. For instance, networks generated by preferential attachment typically place the high-degree vertices in the middle of the network, connecting them together to form a core, with progressively lower-degree nodes making up the regions between the core and the periphery. Many interesting results are known for this subclass of scale-free networks. The random removal of even a large fraction of vertices impacts the overall connectedness of the network very little, suggesting that such topologies could be useful for security, while targeted attacks destroys the connectedness very quickly. Other scale-free networks, which place the high-degree vertices at the periphery, do not exhibit these properties; notably, the structure of the Internet is more like this latter kind of network than the kind built by preferential attachment. Indeed, many of the results about scale-free networks have been claimed to apply to the Internet, but are disputed by Internet researchers and engineers.

As with most disordered networks, such as the small world network model, the average distance between two vertices in the network is very small relatively to a highly ordered network such as a lattice, while the clustering coefficient of scale-free networks can vary significantly depending on other topological details.

It is interesting that Cohen and Havlin proved that uncorrelated power-law graphs, having $2 < d < 3$ will also have ultrasmall diameter $d\, ln(ln(N))$. So, from the practical point of view, the diameter of a growing scale-free network might be considered almost constant.

Although many real-world networks are thought to be scale-free, the evidence remains inconclusive, primarily because the generative mechanisms proposed have not been rigorously validated against the real-world data. As such, it is too early to rule out alternative hypotheses. A few examples of networks claimed to be scale-free include:

- Social networks, including collaboration networks. An example that has been studied extensively is the collaboration of movie actors in films.
- Protein-Protein interaction networks.
- Sexual partners in humans, which affects the dispersal of sexually transmitted diseases.
- Many kinds of computer networks, including the World Wide Web.
- Semantic networks.

1.4 Interdependencies and complex systems

Functional (inter)dependencies in complex systems are, sometimes, very subtle and difficult to be described due the presence of indirect relations and complex feedback paths. Such an issue is further complicated by the usual scarce knowledge about such dependencies or, sometimes, by the inaccurate knowledge of the system structures themselves.

Due to the complexity of the argument, the issue of complex systems' interdependency is going to attract a considerable attention, also for the visible technological, social and biological pervasiveness of such a systems. The "interdependence problem" represents a real metaphor of complexity and, therefore, also "basic" sciences are going to pay a considerable attention the study of these phenomena [R. Albert, A.–L. Barabási, 2002, S. Boccaletti et al., 2006].

As previously described, a great deal of effort has been recently devoted the study and the modelling of complex systems from the standpoint of theoretical analysis. The promise of these efforts is to unveil relevant insights on those systems (growth mechanisms, causes of vulnerability, understanding of their dynamic behaviour under perturbation, onset of emerging phenomena etc.). The ambitious goal of understanding the combined behaviours, i.e. the dynamic behaviour of clusters of inter-dependent complex systems, will open the way to the modelling of groups of complex systems and to the analysis of their behaviour, in order to predict the occurrence (or the insurgence) of critical behaviours triggered by mutual interdependencies. Then, topological analysis made on the bases of the classical graph theory allowed to unveil relevant properties of such a kind of networks, underlining the role played by several components (nodes and arcs) whose topological configuration may strongly influence the nature of the system itself. Indeed, it has been shown also that a *scale-free* structure induces a considerable robustness against *random* faults (or *deaths*) of a given system and, in turn, a great vulnerability with respect to specific (or *aimed*) failures (*or attacks*). It has also been proved that, even if a kind of *Preferential Attachment* is the most common growth mechanism of many real complex systems, the insurgence of *scale-free* structures may be obstacled by the same physical or technological nature of the systems themselves (or of their dynamics), which may limit or modify the way such systems grow or evolve along with the time.

When there is the presence of complex interaction mechanisms, therefore, the plain topological analysis of the systems reveals to be too limiting, expecially for the comprehension of the behaviours deriving from the specific functional characteristics of the interacting elements. Such limitation can be overcome complementing the topological analysys with a *functional analysis*, introducing (often simplified) dynamic models which, qualitatively or quantitatively, may reproduce (or simulate) the behaviour of the elements inside the system analysed.

Such a kind of *functional analysis*, often, is a very hard task whose difficulty is mainly related to the lack of accurate information about the real dynamic models of the system's elements rather than to real technological limits.

For example, in the case of technological complex systems, functional (or "behavioural") models require the knowledge of a very large amount of data; network's graphs must be complemented with the technical, and organizative characteristics of physical nodes, links and requirements etc. These data are often unavailable or, more often, *classified*. By the way, these limits are usually overcome with the development of simplified behavioural models, able capture, with an adequate compromise between abstraction and realism, the basic features of the technological systems and their networks.

Chapter 2

Topology-based models

2.1 Funtional Topology-based models

Taking the move from the mentioned state-of-the-art about plain topological analyses, we developed a functional analysis methodology which takes into account also some specific functional properties of the investigated systems. In order to explore the capabilities of such a methodology, we focused our attention on two very complex technological systems, the Italian Electrical Transmission Network and a long-range TLC network. The first analyses were devoted to understand the behaviour and the robustness of the networks when assumed to operate separately then, we explored the effects of mutual interactions focusing our attention on the degradation of the Quality of Service provided by the networks.

2.1.1 The electrical power network model

We have analysed data relative the Italian high-voltage (380 kV) electrical transmission network (HVIET), depicted in Figure 2.1. This study follows previous works performed to unveil, from a plain topological analysis, a number of features of the HVIET [P. Crucitti, V. Latora, M. Marchiori, 2004, F.

Tiriticco, S. Bologna, V. Rosato, 2006]. Network's data have been inferred from the analysis of the public documentation.

HVIET can be represented by an undirected graph of N nodes and E arcs (also referred "lines"). Available data allowed to attribute to each node, the quality to be a *source* node S (where the power is inserted in the network), a *load* node L (where the power is spilled from the network) or a *junction* node J (when it was neither a S nor a L node). The topology of the HVIET is reported in Figure 2.1 where S nodes are green, L nodes are red and J nodes are black circles. HVIET consists of $N = 310$ nodes and $E = 359$ arcs. There are $S = 97$ source nodes, $L = 113$ load nodes and $J = 100$ junction nodes. All lines are depicted as *single* lines, also when they are *double* (i.e. two point-to-point connections). Points of cut of the network (which is connected other european electric networks) have been substituted by "fictitious" source nodes, where the same amount of electrical power received from foreigner countries is introduced into the network.

Several topological properties have been analysed on the HVIET network and, among them, the distribution $P(k)$ of the node's *degree* k (the *degree* is the number of links connecting each node its nearest neighbours). The HVIET $P(k)$ is reported in Figure 2.3 [R. Albert, A.–L. Barabási, 2002, P. Crucitti, V. Latora, M. Marchiori, 2004]. From the analysis of $P(k)$ we observed that the network has a limited number of hubs, whose maximum degree is $k_{max} = 10$; $P(k)$ and the cumulative degree distribution $P(k > K)$ both likely fit an exponential rule (which could indicate the existence of a single–scale network [R. Albert, I. Albert, G.L. Nakarano, 2004]). The $P(k > K)$ can be fitted with $e^{-0.55K}$, in agreement with previous findings for the North-american power grid [R. Albert, I. Albert, G.L. Nakarano, 2004]. The average *clustering* coefficient C has resulted to be small $C = 2.06 \cdot 10^{-2}$.

Taking the move from [V.Rosato, L.Issacharoff, S.Bologna, 2004], were a complete study about topological properties of HVIET allowed to identify specific sites for the HVIET *structural* vulnerability points, we focused

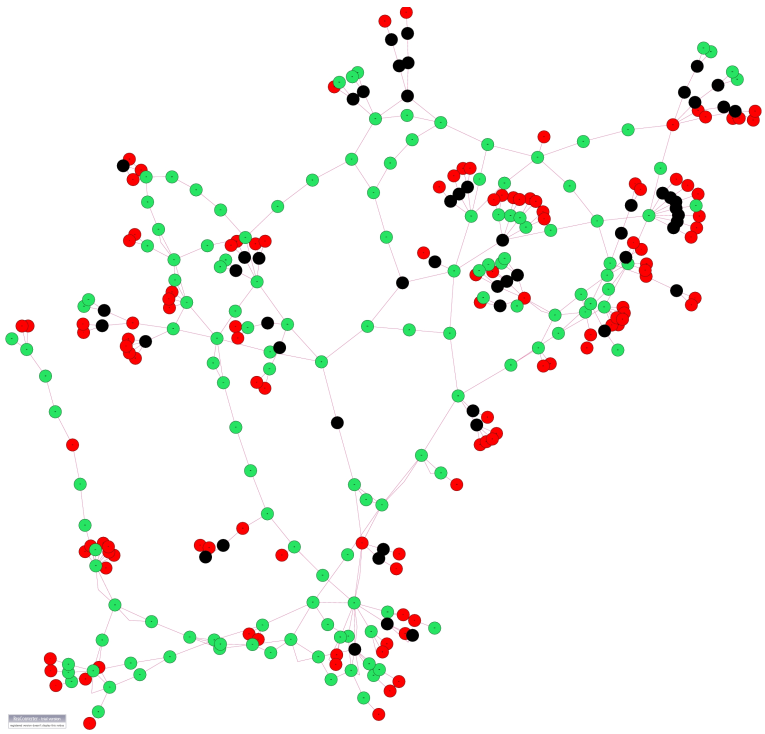


Figure 2.1: The graph corresponding to the HVIET network. Source nodes are depicted as green circles, Load nodes are red and Join nodes are black.

Figure 2.2: The Italian high-voltage (380 kV) transmission grid.

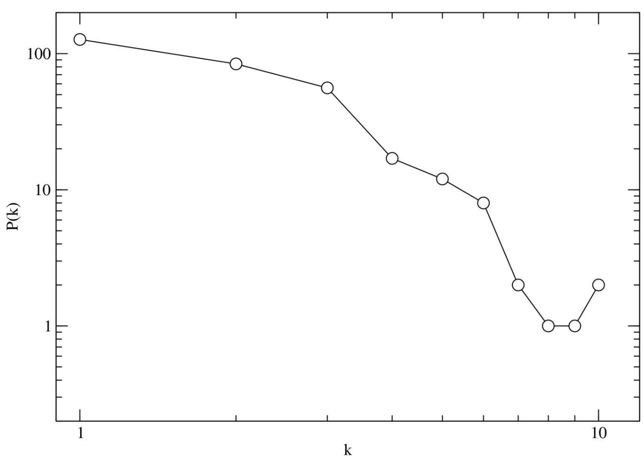


Figure 2.3: The distribution of HVIET node's degree (log–log scale).

our attention into the *structural* vulnerable sites with respect the functional caracteristics of the HVIET.

Then, our aim was to unveil if *structural* and *functional* vulnerability were somehow related to the same sites (i.e. nodes and lines) or, instead, *functional* vulnerability (i.e. the sites whose fault produces the highest damage in terms of reduction of operability) was associated to a different set of sites.

In order perform this assessment, we used the well known DC power flow model (whose details are discussed in the appendix 5.4), which permits to evaluate the state of a power network in terms of power flow over its links, as a result of a linear combination of the power inputs and the power outputs over the network. Moreover, we focused the study on the influence of the network topology on the steady–state power flow rather than on transitory regimes. To do so, we will firstly evaluated the power flow distribution on the unperturbed network, resulting from a specific input–output condition, chosen to be representative of a typical power requirement that HVIET must daily sustain. Then we perturbed the network, by removing links, and verify if the "damaged" network was still able produce a correct response to the input-output demand within the imposed physical constraints.

2.1.2 Perturbation Analysis

The cut of one or more links in the HVIET induces a modification into flow allocation on the network that might be still evaluated using eqs. (5.3) and (5.1). For some cuts, however, a solution is inhibited by the physical constraints. In other terms, due to overload conditions or unbalancing situations, the electric grid is no more able to supply energy from the source to the destination nodes. This would imply the presence of more or less large blackouts if any corrective action is taken. In accordance with typical policies adopted by electrical operators to prevent this condition, we reduce the energy extraction from the network, and consequently the energy injected in it, by a suitable modulation of the loads. This procedure is named *re-*

dispatching. To this end, we have added to the model a procedure able to evaluate the new input conditions P in order to satisfy eqs. (5.1) and (5.3) with the constraints (5.4), by further optimising the distance with respect to the "normal" load conditions $P^{(0)}$. In other words, P is searched such that ΔP, defined

$$\Delta P = \sum_{i \in loads} [P_i - P_i^0] \tag{2.1}$$

results to be minimum. This strategy allows to find a new solution, although degraded, of the network flow. The vector P_i will be thus the new solution of the dispatching problem [V. Rosato, L. Issacharoff, S. Bologna, 2006]. In [V. Rosato, L. Issacharoff, S. Bologna, 2006] it is assumed that the "distance" of this new solution with respect to the normal distribution is a measure of the quality of service of the HVIET in the perturbed condition. Specifically a suitable "Quality of Service" QoS of the network has been defined as a function of the perturbation strength ξ (measured in terms of broken lines) as follows:

$$QoS = 1 - \frac{\Delta P}{\sum_{i \in loads} P_i^0} \tag{2.2}$$

Fig. 2.4 reports the QoS as a function of ξ either in the case in which "re-dispatching" is performed (circles) and when it is not performed (diamonds). In the latter case, QoS is set to zero when the system cannot be solved or set to one if the system has a solution within the physical constraints. Data reported in Fig. 2.4 refers to average over a large number of different choices of removed lines. Fig. 2.4 also shows that an (ideally) optimized redispatching strategy of the input and the extracted power could reduce the impact of faults: the decrease of QoS, in fact, could be minimize (in principle) to a few percent also in case of a severe network perturbation (like, e.g., the simultaneous removal of one or two lines).

Stefano De Porcellinis

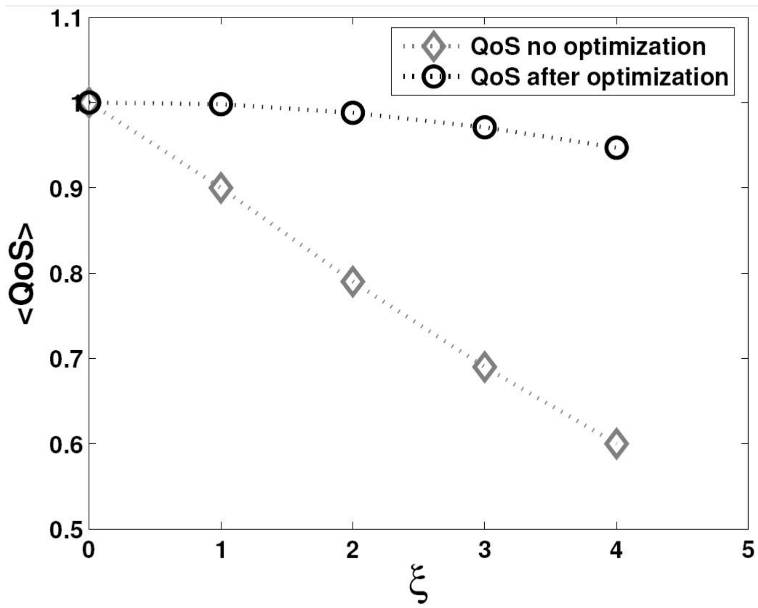


Figure 2.4: QoS values as a function of the perturbation ξ (number of removed lines). Squares represent the QoS values when no optimization is performed; circles when redispatcing is performed.

Stefano De Porcellinis

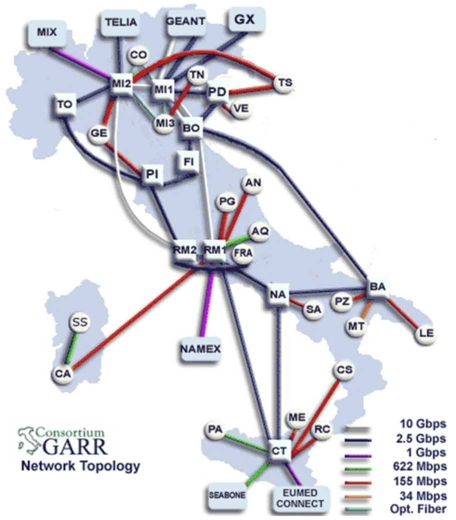


Figure 2.5: The high–bandwidth backbone of the Internet network dedicated link Italian universities and research institutions (GARR).

2.1.3 The GARR model

We have chosen to investigate the traffic dynamics on the Italian high–bandwidth backbone of the Internet network dedicated to universities and research institutions (GARR)[1] depicted in Figure 2.5.

The GARR graph, inferred from public documentation [2] consists in the adjacency matrix of the (undirected) graph $G(N, E)$ of N nodes and E arcs ($N = 39$ and $E = 58$). The network is quite small and its reduced dimension does not allow to make a clear topology analysis of its structure. The implemented functional model of the network is able simulate the travel of small data packets from an Origin Node (ON) to a Destination Node (DN). The size of data packets is supposed be infinitesimal, according to the hypothesis of an infite bandwidht of the communication lines.

[1]GARR (whose acronym means "Gestione Amplimento Rete Ricerca" - "Research Network Widening Management") is composed by all subjects representing the Italian Academic and Scientific Research Community.

[2]www.garr.it

The dynamical model issued for describing the functioning of the network is based on the following assumptions:

- each node is supposed to represent an AS–level router; such a node, at each simulation–step, might perform two basic actions:
  - send a data packet to a neighbour node
  - receive one or more data packets from neighbour nodes.

  A node cannot send a data packet itself. These hypotheses stem from the fact that all nodes are supposed to have equal technological properties *independently* on their *connection degree*. This can be reasonably supposed because the GARR backbone is quite small and all the nodes have very similar *connection degrees*;

- each node contains two basic elements: (a) a buffer (unlimited in size) allowing the received packets to form a queue and (b) a routing table (RT) which, for each node i, associates, for each DN k, two different nodes j_1 and j_2, both belonging to the nearest neighbours of node i, and each of them being part of a different minimum–path for reaching the DN. The transit packet will be directed toward one of these two nodes: the choice between the direction j_1 or the direction j_2 is made according to the probabilistic rule [P. Echenique, J. Gomez-Gardenes, Y. Moreno, 2004]:

$$P(j_1) = \frac{e^{-\beta X_{j_1}}}{e^{-\beta X_{j_1}} + e^{-\beta X_{j_2}}} \tag{2.3}$$

$$P(j_2) = \frac{e^{-\beta X_{j_2}}}{e^{-\beta X_{j_1}} + e^{-\beta X_{j_2}}} \tag{2.4}$$

  where $X_k, k = j_1, j_2$ is the number of data packets sent node k and $P(j_1) + P(j_2) = 1$.

- packet dispatching takes place a FIFO strategy: packets queued in the buffer are treated the $First - in$, $First - out$ policy.

Each data packet contains the value of two different quantities: the time

Stefano De Porcellinis

of emission and the address of the DN. Both of these information are used to route the data packet throughout its journey, until the DN.

The amount of traffic present in the network is measured by the variable λ, which measures the frequency with which each node emits a data packet. According to such a definition, for example, $\lambda = 0.1$ represents the level of traffic when, at each time step, 10% of the N nodes of the network generate a data packet directed toward an equal number of DNs.

The traffic simulation on the network starts with the network empty. All buffers are empty and no data packets are in the network. At a given starting time $t = 0$, each node emits, with a probability of λ a data packet directed to a randomly chosen DN. Each node directs the packet to one of its neighbouring nodes according to its *Routing Table* (RT) and the probability defined in eqs. (2.3),(2.4). Data packets are immediately received by that node and placed into the buffer. At the next step $t = 1$, the packet creation is repeated. If a node does not create a new packet, it can forward the first packet residing in its buffer (i.e. that which arrived at first among the others) towards one of its neighbouring nodes (according to the RT). If, in turn, it gives origin to a further event of data creation, the dispatch of the new data packet is performed and the buffer's packets are kept in stand–by; they are be processed as soon as the node does not give origin to a new packet.

This dynamic is iterated for a large number of timesteps. Packets are received by their destination nodes after a certain *delivery* time τ which varies along with the distance ON–DN, the network's topology and, particularly, the traffic level λ. If λ is quite high, one expects that nodes frequently originate new packets and, thus, cannot promptly deliver previously received data packets, which thus starts to fill the node's buffer. An average indicator of the efficiency of the network is represented by the value of the "average delivery time" $< T >$; if the network produces M packets, whose m are correctly delivered within the simulation time Γ, then

$$< T >= \frac{1}{m} \sum_{i=1}^{m} \tau_i \tag{2.5}$$

where τ_i is the delivery time of the packet i.

The dynamical behaviour of the network, produced by the action of the basic transmission rules introduced into the model, produces a traffic which, as a function of the traffic level λ, can be ascribed to two different phases: a first phase, at $\lambda < \lambda_c$, where the $< T >$ behaviour is a (slowly) linearly increasing function of λ. When $\lambda > \lambda_c$ a *congested* phase takes place, producing a rapid and not linear increase of $< T >$. The congested phase originates by the presence of buffers which, for enough large traffic values (depending on network size and topology) start to fill out at a rate larger than the rate to which they discharge.

A typical behaviour of the quantity $< T >$ a function of the traffic λ for our model of the GARR network is reported in Figure 2.6.

Also in this case, the behaviour of the system under the presence of structural faults could be measured. If one removes one (or more) links, one can evaluate the behaviour of the network in terms on the new form of $< T >$ a function of λ [V. Rosato, L. Issacharoff, D. Caligiore, F. Tiriticco, S. Meloni, 2004].

2.2 Coupled technological systems

Taking the move from the state-of-art previously mentioned, we developed a methodology to analyse the effects of mutual interdependencies among the mentioned technological systems.

These networks have been made interacting using an interaction matrix built up on a geographical basis: GARR's nodes operativeness has been related to the load–level of the neighbouring electrical network's nodes (i.e.

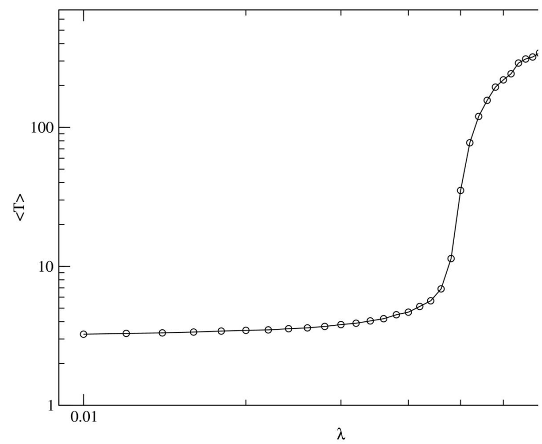


Figure 2.6: Log–log scale representation of the behaviour of the average delivery time $< T >$ a function of the traffic level λ ($0 \leq \lambda \leq 1$) in the unperturbed GARR network, predicted by the dynamic model.

if the electrical power level of a node is lower than a threshold, then all the communication nodes depending from the node are disconnected).

Then, in order to evaluate how a perturbation affecting the electrical transmission network (resulting in its partial operability loss) propagates on the Internet network (producing a service degradation) we analysed the effects produced by the reduction of the electrical power network's *Quality of Service* on *QoS* of the communication network.

The interdependency of the two networks has been modelled by making the hypothesis that nodes of the two networks, which are "geographically" close, are functionally related. Then, according to its geographical position, a GARR node has been functionally connected to the closest HVIET load node in the region. We assumed, also, that a GARR node is connected to a single HVIET load node, whereas a single HVIET load node can be linked to more than one GARR node.

For each load node of HVIET, we determined the unperturbed value of the extracted power, on the basis of the solution of the dispatching problem arising from the normal input condition $\mathbf{P^{(0)}}$ and assumed that, under this condition, all the GARR nodes were correctly supplied (i.e. all the GARR nodes were in the `on` state). If, in turn, any fault affects the HVIET network; we evaluate the power P_i dispatched to the load nodes and we compare it with the expected power $P_i^{(0)}$. We define that a GARR node k is in its `on` state if the actual dispatched power for the correspondent load node i is such that

$$\text{GARR node } k = \begin{cases} \texttt{on} & \text{if} \quad P_i \geq \alpha P_i^{(0)} \\ \texttt{off} & \text{otherwise} \end{cases} \tag{2.6}$$

where $0 \leq \alpha \leq 1$ is a suitable parameter which determines the strength of the "coupling" between the two networks. In other words, if the electrical node is not able to dispatch a sufficient power (i.e. at least the α fraction of the normal power) then the communication node is switched–off and the GARR network results be perturbed. This is a realistic assumption: in fact, in case of a dispatching problem from the electrical side, it is reasonable to suppose that several users connected to the node on the low voltage distribution network supplied by that node will be put in blackout. The parameter α here introduced allows to vary the amount of QoS which the router is able to accomodate: if α is close to one, it will be suffcient a slight reduction of the dispateched power to put the router in its off state. Coversely, if α is small, the router can accomodate a large decrease of the dispatched power. In absence of an unavailable realistic figure, we have set the α value to an intermediate value of $\alpha = 0.75$ which should represent a reasonable trade-off between a strong interdependence coupling (α close to one) and a substantial absence of interdepedence (with α close to zero).

2.2.1 Simulations and results

We have performed the following simulation: we perturbed the HVIET network by randomly removing a line ($\xi = 1$) and, for each instance, we evaluated if eq (5.3) was fulfilled for the normal load condition $\mathbf{P}^{(\mathbf{0})}$. If it was not the case, we used the re–dispatching procedure to evaluate the new power dispatched for the load nodes. For each final configuration of loads, we evaluate the corresponding configuration of the GARR network, where all the GARR nodes supplied by HVIET load nodes with a power lower than the threshold indicated in eq. 2.6 are put in the `off` state. Then, such a perturbed configuration was used to host a traffic simulation, in order to evaluate the $< T >= f(\lambda)$ function. In the case when the GARR network resulted to be disconnected, the value of $< T >$ was arbitrarily set to the maximum value that it assumed at largest values of λ (i.e. the value of $< T >= f(\lambda = 0.1)$ in fig 2.6).

Successively, we performed the same analysis removing, from HVIET, two ($\xi = 2$) and three ($\xi = 3$) lines at once.

For each value of the perturbation $\xi = \{1, 2, 3\}$, we evaluate the response of the GARR system as the average on the different configurations issued upon the HVIET faults. In Figure 2.7 we reported the result for different perturbation strengths ($\xi = 1 - 3$) and for the value of $\alpha = 0.75$ (this means that a GARR node is put in the `off` state only if the power received by the load node, to which it is connected, was lower than the 75% of the normal power).

Fig. 2.7 shows that the effect of the perturbation on the GARR network consists in the increasing of the average delivery time under the"normal" regime, while the critical traffic level λ_c, where the congested phase onsets, remains practically unchanged. This marked effect in the region of "normal" regime depends on the fact that, due to the small size of the GARR network, even with an intermediate coupling parameter α, even a small degradation of the electrical load might result in the disconnection of the GARR network. In that case, according to what previously stated, the whole function $< T >=$ $f(\lambda)$ is set to a large value of $< T >$; when averaged with the results of all the simulations performed for a given perturbation strength ξ of the electrical

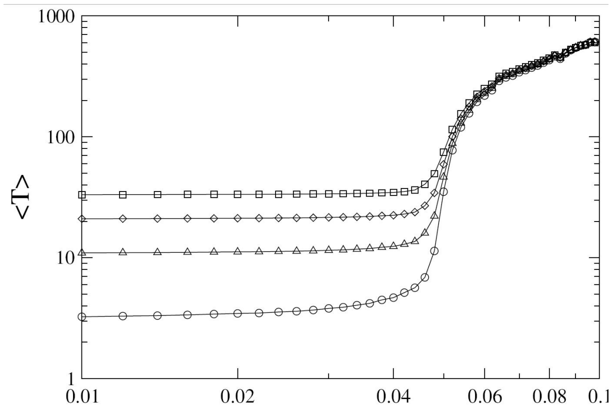


Figure 2.7: Log–log scale representation of the behaviour of the average delivery time $< T >$ as a function of the traffic level λ $(0 \leq \lambda \leq 1)$ in the unperturbed GARR network (circles), $\xi = 1$ (triangles), $\xi = 2$ (diamonds), $\xi = 3$ (squares). The value of the parameter α of eq. 2.6 has been set 0.75.

network, this condition increases dramatically the average delivery time in the "normal" regime.

The relative impact of one network on the other could be directly measured by resorting the definition of CI's *Quality of Service* (QoS). If we define QoS of the electrical infrastructure the value [V.Rosato, L.Issacharoff, S.Bologna, 2004]

$$QoS_{EL} = 1 - \frac{\sum_{i \in loads}[P_i^{(0)} - P_i]}{\sum_{i \in loads} P_i^{(0)}} \tag{2.7}$$

and QoS of the communication infrastructure

$$QoS_{TLC} = \frac{\frac{m}{M}}{\frac{<T>}{<T_0>}} \tag{2.8}$$

where m and M are, respectively, the number of the generated and dispatched data packets and $< T >$ and $< T_0 >$ are, respectively, the average delivery times (during the normal phase) for the perturbed and the unperturbed network. Then, we can rationalize the interdependency between the two

Stefano De Porcellinis

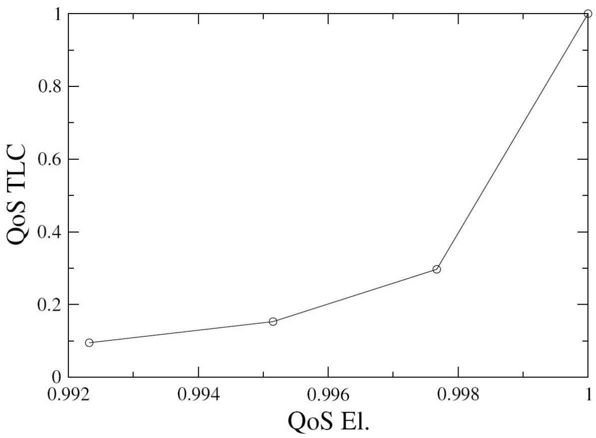


Figure 2.8: Variation of the QoS value for the communication infrastructure ($QoSTLC$) respect the variation of the QoS of the electrical network ($QoSEL$).

networks representing the QoS of a network with respect to a function of the other network's QoS(Figure 2.8).

Chapter 3

Holistic models

Functional analysis, coupled with the topological one, allowed to explore some characteristics and behaviours of complex systems, especially when analitical or simplified models can be defined for the elements of the systems. Moreover, the coupling of multiple functional models, in a scenario containing different kinds of systems, also interacting each other, seem to be feasible. However, such kind of analysis is not easily achievable when the models of the element are still not completely understood or an higher level of abstraction is required in order to describe the interactions among the whole systems. To this last end, modeling approaches which tend to obscure the role played by the single components of the systems and that represent only the higher level interactions among the latters, may result more successful. Moreover, in the presence of wide and (also geographically) spread systems, holistic models may catch more easily the overall behaviour of the "system of systems" and the dynamics which drive the cooperation among the systems. One of the most interesting holistic approaches, inspired by the works of the Economy Nobel's Prize Wassily Leontief, is the Input-Output Inoperability Model, initially developed by Haimes and colleagues [Y. Haimes, P. Jiang, 2001, Y.Y. Haimes, B.M. Horowitz, J.H. Lambert, J.R. Santos, K.G. Crowther, C. Lian, 2005, Y.Y. Haimes, B.M. Horowitz, J.H. Lambert, J.R. Santos, C.Lian, K.G. Crowther, 2005].

3.1 Input-output Inoperability Model

Input-output Inoperability Model (IIM) is a framework that enable to analyse, using an high level of abstraction for the representation of the of entire systems, of the how the presence of dependencies and interdependencies among different systems may facilitate the spreading of degradations [Y. Haimes, P. Jiang, 2001, K.G. Crowther, Y.Y. Haimes, 2005].

The IIM uses the same framework proposed by Leontief, but instead to consider how the production of goods or services of a firm influences the level of production of the other firms, it focalises its attention on the spreading of "degradation" into a networked system. To this end, they introduce the concept of inoperability, defined as the inability of a system to perform its intended functions, and analyse how a given amount of inoperability inside one element influences the other components of the network. In [Y.Y. Haimes, B.M. Horowitz, J.H. Lambert, J.R. Santos, K. Crowther, C. Lian, A. Srinivasan, 2004] the authors used this approach to analyse how inoperability induced by a High Altitude Electromagnetic Pulse (HEMP) affects the different sector of US economy and to estimate the recovery time under different hypothesis, while in [S. Panzieri, R. Setola, 2008] the approach is modified to explicitly consider also the spreading of failures. The great interest around this approach is related to its simplicity, even if the results that it provides are, for many aspects, largely qualitatively and oversimplified.

In a nut–shell, the approach assumes that each system can be modeled as an atomic entity, whose level of operability depends, further than from external causes, on the availability of "resources" supplied by other systems. An event (e.g., a failure) that reduces the operational capability of the i-th system, may induce degradation also in the systems that require goods or services produced by the i-th one. These degradations, then, may be further diffused in a cascade–fashioned effect and, eventually, exacerbate the situation of the i-th one due to the presence of feedback loops.

Mathematically, IIM describes everything on the base of the level of inoperability associated to each system. The inoperability of the i-th systems is coded via the variable x_i defined in the range $[0,\ 1]$; where $x_i = 0$ means that the systems is fully operative, while $x_i = 1$ means that the systems is completely inoperable.

Neglecting any restoring dynamic, an estimation of the overall impact induced on the whole system–of–systems by an external cause can be calculated as the steady-state solution of

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{c} \tag{3.1}$$

where $\mathbf{x} \in [0,1]^n$ and $\mathbf{c} \in [0,1]^n$ are the vectors composed, respectively, by the level of inoperability and by the external failure degree associated with each one of the n different systems considered. $\mathbf{A} \in \mathcal{R}^{\backslash\S\backslash}$ is the matrix of the technical coefficients of Leontief. Specifically, a_{ij} represents the inoperability induced on the i-th system by the complete inoperability of the j-th one. Obviously, if $a_{ij} < 1$ the i-th system suffers of an inoperability smaller than the one exhibited by the j-th system, while if $a_{ij} > 1$ there is an amplification in the level of inoperability. By construction $\mathbf{A}$ has the peculiarity that $a_{ii} = 0 \ \forall \ i = 1, \ldots, n$.

In [R. Setola, 2007], to better quantify the role played by each economical sector, the author introduces the *dependency index*, defined as the sum of the Leontief coefficients along the single row

$$\delta_i = \sum_{j \neq i} a_{ij} \qquad \text{(row summation)} \tag{3.2}$$

and the *influence gain*, i.e., the column sum of the Leontief coefficients

$$\rho_j = \sum_{i \neq j} a_{ij} \qquad \text{(column summation)} \tag{3.3}$$

These indices represent a measure of, respectively, the resilience and the influence that the inoperability of given system has on the whole system–of–systems. Specifically, if the associated *dependency index* is smaller than 1, the i-th system preserves some working capabilities (e.g., thanks to the presence of stocks, buffers, etc.) in spite of the level of inoperability of its suppliers. On the other side, when $\delta_i > 1$ the operability of the i-th system may be completely nullified even if some of its suppliers have residual operational capabilities. From the opposite point of view, a large value of the *influence gain* means that the inoperability of j-th system will induce significant degradations on the whole system–of–systems. Indeed, when $\rho_j > 1$ the negative effects, in terms of inoperability, induced by cascade phenomena on the other systems are amplified. The opposite happens when $\rho_j < 1$.

3.1.1 A Methodology to estimate IIM parameters

In order to identify IIM parameters in a scenario including the systems–of-systems of the italian economical sectors, we exploited the experience of several experts (in different sectors) though the use of an ad–hoc set of questionnaires.

Specifically, we estimated the Leontief coefficents of the interdependency matrix A, with the help of several experts who were invited to evaluate the negative effetcs, on "their sector", which could be induced by the complete absence of the services provided by other sectors.

To this end, sector specific questionnaires have been submitted and each expert has been invited to quantify the impact using the linguistic expressions reported in Table 3.1.

Moreover, the experts had to qualify their confidence about the evaluations provided, using the scale of Table 3.2.

Table 3.1: Impact estimation table.

Impact	*Description*	*Value*
nothing	the event does not induce any effect on the infrastructure	0
negligible	the event induces some very limited and geographically bounded consequences on services that have no direct impact on the infrastructure's operativeness	0,05
very limited	the event induces some geographically bounded consequences on services that have no direct impact on the infrastructure's operativeness	0,08
limited	the event induces consequences only on services that have no direct impact on the infrastructure's operativeness	0,10
some degradations	the event induces limited and geographically bounded consequences on the capability of the infrastructure to provide its services	0,20
circumscribed degradation	the event induces geographically bounded consequences on the capability of the infrastructure to provide its services	0,30
significant degradation	the event significantly degrades the capability of the infrastructure to provide its services	0,50
provided only some services	the impact is such that the infrastructure is able to provide only some essential services	0,70
quite complete stop	the impact is such that the infrastructure is able to provide a subset some essential services only to some limited geographically areas	0,85
stop	the infrastructure is unable to provide its services	1

Table 3.2: Estimation confidence scale.

Confidence	*Description*	*Value*
+	Good confidence	0
++	Relative confidence	$\pm\ 0,05$
+++	Limited confidence	$\pm\ 0,10$
++++	Almost uncertain	$\pm\ 0,15$
+++++	Completely uncertain	$\pm\ 0,20$

Notice that, the information about the numerical values associated with each entry in the tables were not provided during the interviews. The conversion from labels to numerical values has been performed in a second time, together with representatives of Government agencies involved in emergency preparedness and security.

Finally, experts were invited to repeat the same exercise considering five different time slots, hence to estimate the impact on their infrastructure when the absence of the services has a duration of: a) less than 1 hour; b) from 1 to 6 hours; c) from 6 to 12 hours; d) from 12 to 24 hours; and e) from 24 to 48 hours.

In order to aggregate the collected data, a measurement of reliability of the different experts has been introduced, ranking them on the base of their experiences as illustrated in Table 3.3.

In order to translate into manageable quantities data provided by the experts, we used Fuzzy Numbers (FNs). Here, fuzzy numbers were represented according using the same normalised trieangular notation described in 5.4. Then the statement "quite complete stop (++)" provided by the k-th expert about the impact of the absence of the *Electricity* (Id=1) on *Air Transportation system* (Id=2) for a period of time $c = [6h - 12h]$ (being him an expert for this domain of class B), can be translated into the FN

$$a_c^k(2,1) = \begin{bmatrix} 0,8 & 0,85 & 0,9 & 0,9 \end{bmatrix} \tag{3.4}$$

Table 3.3: Expert reliability rate.

Class	*Description*	*Value*
A	Expert with large operative experience and with good knowledge of the whole infrastructure	1
B	Expert with operative experience and with some knowledge of the whole infrastructure	0,9
C	Expert with large operative experience but with a specific/bounded point of view	0,8
D	Expert with operative experience but with a specific/bounded point of view	0,7
E	Expert with large (theoretical) knowledge of the whole infrastructure (e.g., university professors)	0,6
F	Expert with large (theoretical) knowledge of some relevant elements of the infrastructure (e.g., university professor)	0,5

where the superscript indicates the expert, the subscript the time period of reference.

Information provided by the experts related to the same quantities have been combined in order to estimate the entries of the Leontief matrix. Specifically, we adopted the following composition law:

$$a_b(i,j) = \begin{cases} lm = min_k \quad \{a_b^k(i,j).l\} \\[2ex] l = \dfrac{\sum_k a_b^k(i,j).l \;\cdot\; a_b^k(i,j).h}{\sum_k a_b^k(i,j).h} \\[2ex] m = \dfrac{\sum_k a_b^k(i,j).m \;\cdot\; a_b^k(i,j).h}{\sum_k a_b^k(i,j).h} \\[2ex] u = \dfrac{\sum_k a_b^k(i,j).u \;\cdot\; a_b^k(i,j).h}{\sum_k a_b^k(i,j).h} \\[2ex] um = max_k \quad \{a_b^k(i,j).u\} \\[2ex] h = max_k \quad \{a_b^k(i,j).h\} \end{cases} \tag{3.5}$$

where, in order to evaluate l, m and u, data provided by each expert have been weighted for the expert reliability index (stored in the h value of the corresponding FN).

Notice that, in order to better accommodate information collected during the interviews, we have "arbitrarily" extended the triangular representation of FNs to a form using up to 6 parameters, including also lm (min lower) and um (max upper). Even if this generalisation presents some theoretical issues we are still investigating, it enable us to pin down two relevant aspects. First, considering into the model both u and um (l and lm, respectively) enabled us to estimate both the most believable worst situation and the most pessimistic one (the most believable best situation and the most optimistic one). Second, comparing u and um (l with lm) we could obtain information about the data coherence. Indeed, $lm \ll l$ or $u \ll um$ meant that some experts have had supplied extremely dissenting data. In this situation, we were warned about the need to perform further analyses in order to understand the origin of these inconsistencies.

	lm	l	m	u	um	lm	l	m	u	um	lm	l	m	u	um	lm	l	m	u	um
	Air transportation					**Electricity**					**TLC (wired)**					**TLC (wireless)**				
Air transportation						0,00	0,27	**0,29**	0,31	0,70	0,05	0,49	**0,50**	0,51	0,70	0,00	0,25	**0,26**	0,29	0,50
Electricity	0,00	0,00	**0,00**	0,00	0,00						0,08	0,23	**0,25**	0,28	0,50	0,00	0,07	**0,08**	0,10	0,20
TLC (wired)	0,00	0,01	**0,01**	0,02	0,05	0,00	0,11	**0,14**	0,18	0,60						0,00	0,02	**0,04**	0,08	0,15
[illegible]less)	0,00	0,00	**0,00**	0,03	0,05	0,00	0,13	**0,17**	0,21	0,60	0,00	0,22	**0,23**	0,24	0,50					

Table 3.4: Leontief matrix for the scenario "a) less than 1 hour". Each entry is a FN codified via [lm l m u um] (with the main value in bold face). The reliability parameter h was omitted for brevity being 1 for all the entries.

3.1.2 Implementation

Staring from 54 questionnaires (from 150 identified experts related to 15 different infratructures), we focused in a first instance our attention on the analysis of the interdependencies among four sectors, whose data have been retrived from 16 interviews: 6 for 1 - *Air Transportation*; 5 for 2 - *Electricity*; 7 for 3 - *TLC (wired)*; and 6 for 4 - *TLC (wireless)*.

The estimated Leontief coefficients for the case "a) less than 1 hour" and for "e) form 24 to 48 hours" are reported, respectively, in Table 3.4 and Table 3.5.

Looking at the matrices we noticed that, while for some entries there was a good accordance between the experts, for others there were very large discrepancies. This phenomena depends, further than from the intrinsic estimation's difficulties, also from the different perspective undertaken by each expert. Indeed, each expert look at the infrastructure from his specific point of view, hence estimating the consequences on the base of those variables that were most valuable for his business. Hence, for example, for the air-transportation (that resulted as the most inhomogeneous sector) we recorded discrepancies between data provided by land-site, air-site and flight-company experts. These discrepancies coud be partially explained taking into account that, for each one of these experts, the term *air-transportation* assumed slight different meanings, implying that the output variables they considered as the most relevant ones were not the same.

	Air transportation					Electricity					TLC (wired)					TLC (wireless)				
	lm	*l*	*m*	*u*	*um*	*lm*	*l*	*m*	*u*	*um*	*lm*	*l*	*m*	*u*	*um*	*lm*	*l*	*m*	*u*	*um*
Air transportation						0,00	0,73	**0,73**	0,74	1,00	0,35	0,83	**0,89**	0,93	1,00	0,00	0,45	**0,49**	0,54	1,00
Electricity	0,00	0,01	**0,01**	0,01	0,05						0,50	0,61	**0,64**	0,64	1,00	0,08	0,10	**0,15**	0,19	0,30
TLC (wired)	0,00	0,12	**0,13**	0,15	0,50	0,00	0,53	**0,61**	0,67	1,00						0,00	0,17	**0,22**	0,28	0,50
TLC (wireless)	0,00	0,01	**0,02**	0,07	0,13	0,45	0,74	**0,79**	0,81	1,00	0,00	0,58	**0,64**	0,66	1,00					

Table 3.5: Leontief matrix evaluated for the scenario "e) from 24 to 48 hours". Each entry is a FN codified via $[lm\ l\ m\ u\ um]$ (with the main value in bold face). The reliability parameter h is omitted for brevity being 1 for all entries.

Examining the time history of all the entries (see Figure 3.1), it results evident that the unavailability of all the services always grows with the time. Moreover, we noticed that in all the cases, the lower l and upper u values were quite close to the most 'believed' value m. This emphasised that, even in the presence of ill-formed data, our methodology had been able to accommodate these uncertainties and provide aggregated data useful for further analysis.

More interesting information can be obtained considering the indexes (3.2) and (3.3). Figure 3.2 shows that the dependency of any infrastructure on external services grows along with the inoperability duration. Moreover, the figure emphasizes that while *Electricity* and *TLC (wired)* preserve in any case residual capabilities to provide services (the index is less than 1), the operability of other sectors, due to the large value of the *dependency index*, might be dramatically compromised.

On the other side, looking to the influence that each infrastructure has on the others, see Figure 3.3, it is evident that the largest influence is exerted by the *TLC (wired)* infrastructure. Such a kind of condition might result a quite counter-intuitive, given that it's a common thought that the most critical infrastructure is the *Electricity*. After a deeper analysis, it was possible to suppose that, being these ones very critical infrastructures, they have specific strategies and device (e.g., UPS) to reduce, for a while, the dependency on electricity provided by national power grid. On the contrary, they seem to be very sensible to the lack of TLC services, being quite impossible to surrogate

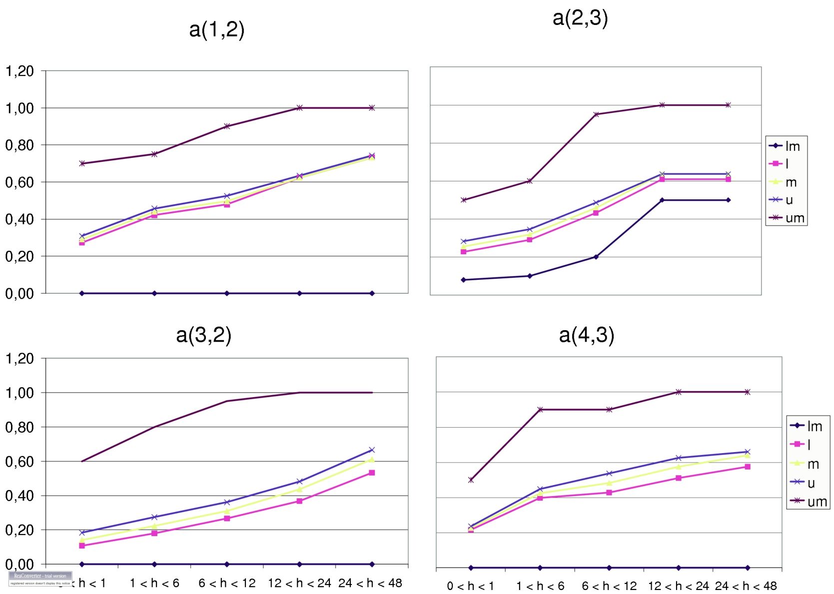


Figure 3.1: Time history of some Leontief matrix's entries.

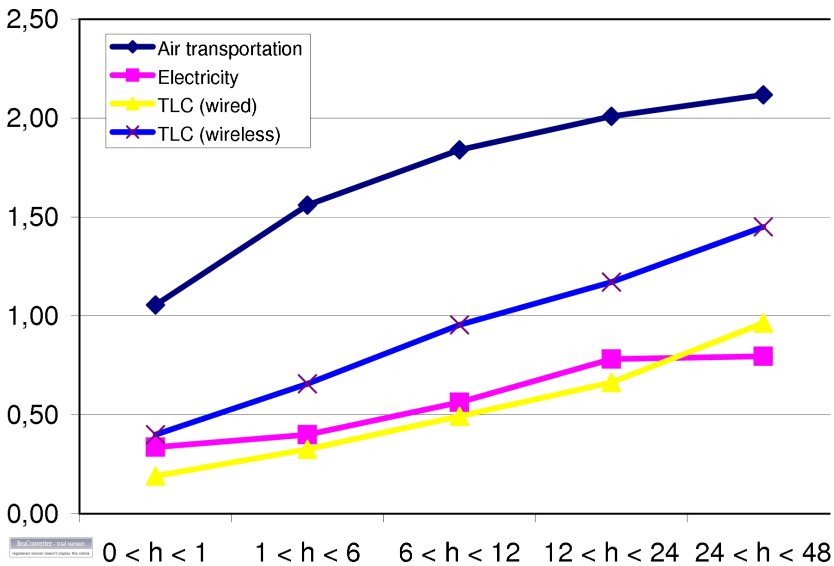


Figure 3.2: Time evolution of the *dependency index* δ associated with the different infrastructures.

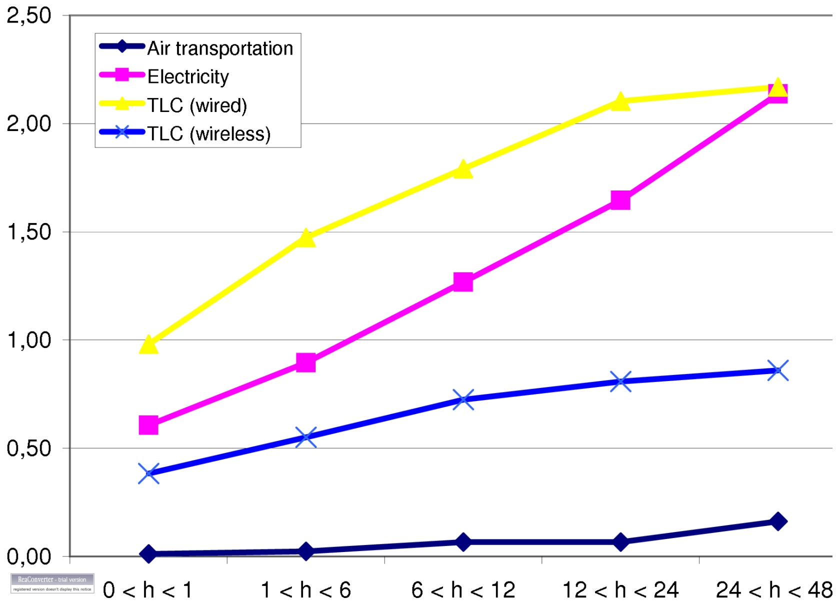


Figure 3.3: Time evolution of the *influence gain* ρ associated with the different infrastructures.

them via local backup devices.

3.1.3 Comments

The approach overcome some of the limits of classical IIM formulation, where the parameters are evaluated using data about economical exchanges. Indeed, such an approach implicitly assumes that the degree of influence of a sector is proportional to the amount of exchanged services, but in many cases this hypothesis did not appear to be adequate.

Then, the developed methodolgy proposes to directly consider the consequences of unavailability of services and to acquire such data from the experience of experts coming from the different sectors, using suitable questionnaires.

Moreover, also the usual approach of interviewing was reverted.

Classical approaches used interviews to acquire information about the de-

Stefano De Porcellinis

pendencies asking for an estimation of the role played by each infrastructure in the whole scenario. Unfortunately, such a kind of approach often leads to inconsistent data, due to the fact that each expert tends to over-estimate the role of his own infrastructure, condition which implies, also, the results to be strongly related to the actual composition of the expert panel.

In our approach, each expert does not have to illustrate how much is crucial his infrastructure, but he is invited to quantify how much *his infrastructure* depends on the services provided by the other or, in other words, to evaluate how much his infrastructure is vulnerable with respect to its providers. Experts shown a good attitude to supply consistent answers to this kind of questions, probably due the nature of their works itself, which obliges them to frquently face with such a sort of issues.

In the following sections some developments of this IIM methodology will be presented, introducing different reference scenarios and closed-loop analyses.

3.2 Health-care scenario

3.2.1 Health-care in a networked framework

Until some decades ago, health-care services were primarily supplied inside hospitals. The patient had to move from his/her home to the hospital, where different diagnostic and therapeutic actions were provided. Moreover, inside the hospital itself the different tools and processes were insulated and autonomous. Patients, and also doctors, have to move from one tool to another, often placed in different areas, to acquire the different resources. Information provided by these tools was generally collected via paper-records. These records were then physically moved (generally in a very poor efficient way) form one side to the other in order to exchange information. In many situations, these records represents the most critical element in the health system due to misunderstanding, errors and lost of information caused by their use. Nevertheless, its main drawback was the difficulty, or even impossibility, to retrieve information from paper records when these need in the future and/or outside the hospital. This situation was largely inefficient especially for the patient point of view. Indeed, he/she had to spent a lot of vast time to move to and from hospital, had to support a great deal of stress to supply more and more time the same information (many often in incomplete, vague or erroneous manner) and eventually to suffer for errors and/or unavailability of information previously stored in some other records. This contributed to increase the social costs of health-care and, in addition with the continuous increment of direct costs of healthcare system, imposed to modify this paradigm. Then we observed, as happened also in many other business sectors, a deep change: the customer (i.e. the patient) has been posed in the centre of a networked system. He has no more need to "physical" move to reach the different providers, but the services themselves are make available "in any time, in any place" suitable customized and via a multitude of channels in order to facilitate their use from the customer. Obviously, in the health care framework, the ubiquitous concepts will be never completely possible neither desirable, but even in this sector we observe the consequences of these changes.

This implies that it is increased the relevance, at least for the end-user, of the service with respect to that of the asset able to provide it. Indeed, in many cases, the user has no information on who (and from where) actually provides the service. This contributes to improve the quality of the services (I am able to offer more qualified and specialised services in spite of geographical location) and, in the same time, to improve efficiency (because it is possible to better distribute loads, and to exploit synergy and scale economy). This revolution is possible because the different elements are no more insulated, but they are components of a network that allows to share information, to support cooperation, to exploit complementary, and to implement

Stefano De Porcellinis

supplementary strategies. However, this new paradigm imposes to assign a different role for the technological infrastructures. In classical hospitals, these infrastructures were not strictly related with the core business (i.e. supply care), but represented only complementary services. Indeed each medical tool was able to autonomously operate without the support of any kind of infrastructure, eventually, with the help of some battery or auxiliary energy power. On the other side, in a modern hospital, some infrastructures, e.g. IT network, represent important and not replaceable components of the system. Especially with the introduction of electronic case history, we observe that the different autonomous and isolated devices have been strongly integrated into a network. This has been obtained exploiting the capabilities of ICT and IP-based connectivity. Moreover, in modern hospitals we observe that even environment parameters (e.g. temperature, humidity), bio-medical devices and infrastructures status are monitored, and in some cases actuated, via IP-based network. Nevertheless, IP network, to correctly operate, needs the presence of other technological infrastructures as electric energy and air conditioning (just to cite two). Even if each one of these infrastructure has been designed with a three like structure (which simplify management and failure impact analysis), due to the presence of many functional relations, the global system appears an intricate and complex graph. In this scenario the presence of feedback mechanisms and cascade phenomena, as illustrated in the next section, largely modify the behaviour of the any component. In addition to in-hospital network, we have to consider that more and more hospitals are supplying e-Health services. Moreover, also some in-hospital services are provided in cooperation with remote structures (e.g. tele-consulting or outsourcing diagnosis). This configures a second type of network where the hospital represents a node of a huge and geographically dispersed system. Notice that, in spite of the previous one, this network is only partially under the control of the hospital but largely depends on external providers. This introduces some new elements generally poorly considered in the manage-

Stefano De Porcellinis

ment procedures (especially that for emergency): Which should guarantee redundancy connections form the hospital until to patient's home? In the presence of failure in the connection link, how the hospital should provide alternative service to e-Health ones? How should be allocated the responsibility for on-site assistance: with a geographical distribution or with other criteria? Not only these and many others questions are without any answer, but in many hospitals no one has still posed this kind of questions even if they provide remote assistance.
Then, to investigate how a networked system is prone to large and catastrophic failures, we used the Input-Output Inoperability Model (IIM) to qualitatively analyse the consequences of a failure inside a modern (highly networked) hospital comparing the results with that of a more traditional (not networked oriented) one.

3.2.2 IIM-based Analysis

In this section, to simplify the analysis we focalise only on the "in-Hospital network" and show that, even considering only this subset, a "small" failure may induce generalised consequences able to concretely affect the capability of the whole hospital to provide health services. To this end, we used again the Input-Output Inoperability Model (IIM), focusing our attention on the analysis of which should be the negative consequence of a failure into the IP-network of a hospital. To this end, we adopted a very crude approximation modelling each technological infrastructure presents within the hospital as an entity which level of operability depends, further to external causes, on the availability of "resources" supplied by other infrastructures. Then, an event (e.g. a failure) that reduces the capability of the $i-th$ infrastructure induces degradation also in those other infrastructures that need of the services or goods produced by the $i-th$ infrastructure. This degradation may propagate involving other infrastructures (cascade) or even exacerbate the negative consequences into the i-th one (feedback). In Haimes et al. (2005) this quantity

Stefano De Porcellinis

is evaluated using the economical statistical data provided by the Bureau of Economic Analysis (BEA). We applied our model to the at–the–time *actual* and *in-building hospitals* of our University. Indeed, at–the–time the CAMPUS had a traditional hospital while a new one, with a very strong modern idea, was under construction. The technological infrastructures on which we focalised our analysis are reported in Table 3.6.

A - water
B - medical gas
C - air conditioning
D - telephone
E - IP network
F - IT infrastructure
G - (electronic) case history
H - bio-medical apparatus monitoring
I - medical alarms
L - electric network
M - infrastructures monitoring (SCADA)

Table 3.6: Technological infrastructures generally present inside an hospital, anconsidered in the analysis.

Analysing the different infrastructures in the modern hospital, it was possible to identify a very complicated web of reciprocal influences, as reported in Figure 3.4. Inside this web, Electric network (L), IP network (E) and Infrastructure monitoring (M) represent hubs with the higher out-degree (i.e. number of outgoing links). This means that these infrastructures have a large influence on the others (they have many non-null terms in the influence gain summation). On the other side, Bio-medical apparatus monitoring (H) has the higher in-degree (i.e. number of ingoing links). Then, the capability of this infrastructures to correctly operate largely depends on the operability of many other infrastructures. Consequently, in the corresponding row of Leontief matrix, there are a lot of not–zero elements, condition which leads

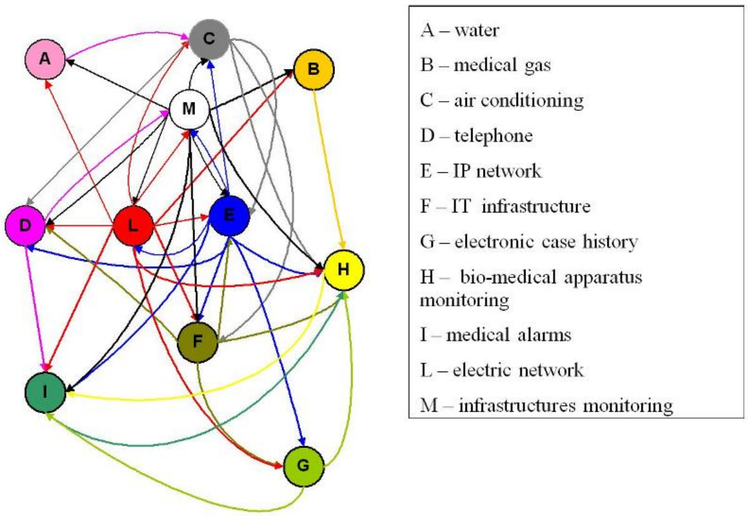


Figure 3.4: Inoperability influence graph for a modern hospital.

to a quite large corresponding dependency index, i.e. δ_H and to the rise of palpable risk of large degradations in correspondence of any failure. However, in order to better understand the role played by the different infrastructures and to identify the most critical elements, we had to consider also the degree of influence that characterised the different links.

To this end, Leontief coefficients associated with traditional and modern hospital have been estimated via interviews, with the managers of the different infrastructures, architects, engineers and with technicians involved in the design of the new hospital. Following an approach similar to the one described in the previous section, this information has been merged with "experiences" coming from doctors and medical assistants. Moreover, as proposed in [S. Panzieri, R. Setola, 2008], we used also schemas and maps of all the infrastructures, in order to evaluate, also, physical, geographical and cyber interdependencies [S. Rinaldi, J. Peerenboom, T. Kelly, 2001]. Comparing the Leontief matrices of Table 3.6 and 3.7, one can notice that (except for the relevance of the telephone network) there is a generalised augment of the influence coefficients in the modern hospital. The dependency index,

	A	B	C	D	E	F	G	H	I	L	M	$\delta_i = \sum_j a_{ij}$
A	0	0	0	0	0	0	0	0	0	0	0,03	0,03
B	0	0	0	0	0	0	0	0	0	0,3	0,1	0,40
C	0,03	0	0	0	0	0	0	0	0	0,6	0,05	0,68
D	0	0	0,10	0	0	0,01	0	0	0	0,15	0,03	0,29
E	0	0	0,15	0	0	0,10	0	0	0	0,3	0,05	0,60
F	0	0	0,20	0	0,25	0	0	0	0	0,2	0,05	0,70
G	0	0	0	0	0	0	0	0	0	0,05	0	0,05
H	0,05	0,15	0,20	0	0,10	0,05	0	0	0,05	0,3	0,05	0,95
I	0	0	0	0,10	0,05	0	0	0	0	0,25	0,20	0,60
L	0	0	0	0	0	0	0	0	0	0	0,07	0,07
M	0	0	0	0	0,03	0	0	0	0	0,08	0	0,09
$\sum_i a_{ij}$	0,08	0,15	0,65	0,10	0,43	0,16	0	0	0,05	2,23	0,63	

Figure 3.5: Leontief matrix for a traditional hospital. Notice that in this case G represents paper-based case history. The matrix has been bordered with the dependency δ_i and influence ρ_i indexes.

that represents a measurement of the robustness of the corresponding infrastructure with respect to the inoperability of the others, for the traditional hospital varies from 0,05 (associated with the paper based Case history (G)) to 0,95 (of the Biomedical apparatus monitoring (H)). Because such a quantity is considerable less than the unit for almost all the infrastructures, we inferred that, in a traditional hospital, the different infrastructures were substantially autonomous, able to correctly supply their services without the need of the resources supplied by the other infrastructures.

At the opposite, in the modern hospital, such a quantity varies from $0,11$, corresponding to Water infrastructure (A), up to $1,89$, related with the Electronic case history (G). Moreover, also Bio-medical apparatus monitoring (H) shows a very high value (1,69). This means that there is a generalised increase of interdependencies but also an augment of fragility, because the failure of any infrastructure has a direct influence on the capability of the other infrastructures to perform their own works. Curiously, the case history

	A	B	C	D	E	F	G	H	I	L	M	$\delta_i = \sum_j a_{ij}$
A	0	0	0	0	0	0	0	0	0	0,05	0,06	0,11
B	0	0	0	0	0	0	0	0	0	0,30	0,13	0,43
C	0,03	0	0	0	0,08	0	0	0	0	0,60	0,08	0,79
D	0	0	0,10	0	0,40	0,10	0	0	0	0,15	0,04	0,79
E	0	0	0,15	0	0	0,18	0	0	0	0,35	0,09	0,77
F	0	0	0,20	0	0,43	0	0	0	0	0,23	0,06	0,92
G	0	0	0	0	0,63	0,87	0	0	0	0,39	0	1,89
H	0,05	0,15	0,20	0	0,24	0,19	0,31	0	0,05	0,42	0,08	1,69
I	0	0	0	0,08	0,09	0	0,02	0,02	0	0,29	0,21	0,71
L	0	0	0	0	0,02	0	0	0	0	0	0,09	0,11
M	0	0	0	0,14	0,04	0	0	0	0	0,22	0	0,40
$\rho_j = \sum_i a_{ij}$	0,08	0,15	0,65	0,22	1,93	1,34	0,32	0,02	0,05	3,00	0,84	

Figure 3.6: Leontief matrix for a modern hospital. Notice that in this case G represents electronic case history. The matrix has been bordered with the dependency δ_i and influence ρ_j indexes.

infrastructure, that in the traditional hospital was one of the less sensitive element with respect to infrastructures' failures, in the modern hospital, where it has been implemented via electronic databases, become one of the most sensitive one.

The level of influence that the different infrastructures exercise (i.e. the influence gain defined as the sum for columns of the Leontief matrix $\rho_j = \sum a_{ij_i}$) varies, for the traditional hospital, from 0 (Case history (G) and Biomedical apparatus monitoring (H)have practically no impact on the other infrastructures), up to 2,23 of the Electric network (L). The larger value of the latter coefficient emphasizes the cornerstone role played by the electricity in the traditional hospital.

Proceeding with the analysis, it is possible to observe that, in the modern hospital, the influence gain varies from 0,02 (associated with the Bio-medical apparatus monitoring (H)), up to the value 3 of the Electric network (L). At the same time, however, the influence gains associated with the IP-network (E) and that of the IT-infrastructure (F) are greater then 1 being, respec-

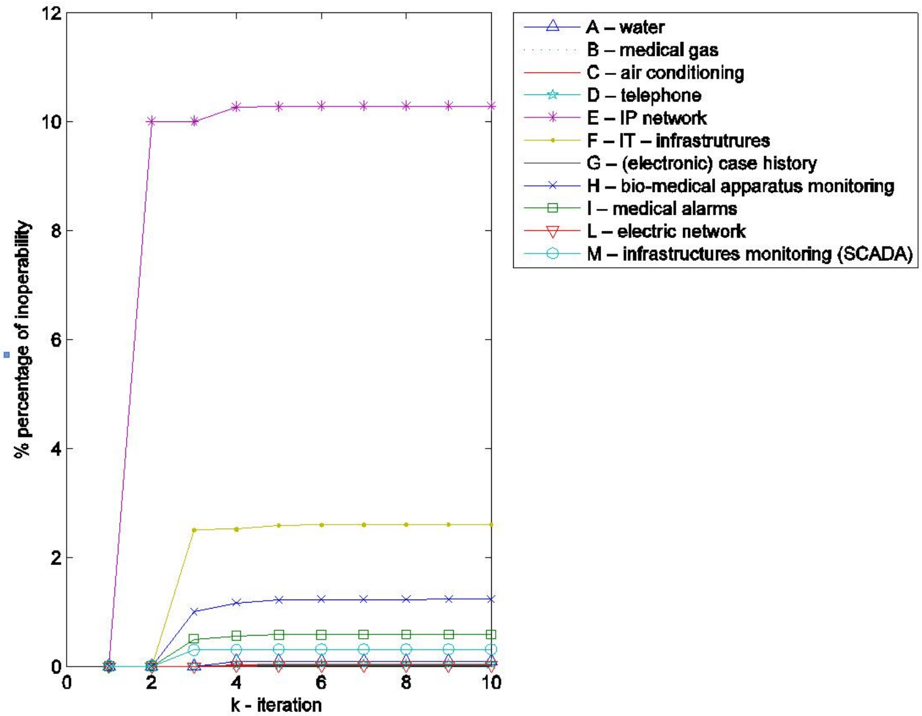


Figure 3.7: Impact scenario induced by a failure that reduces of 10% the operability of the IP-network (E) in a traditional hospital. Notice that in steady state there is a limited increment in the inoperability of the IP-network, while the other infrastructures are quite unaffected (only IT-networks (F) shows a degradation higher than 2%).

tively, equal to 1,93 and 1,34. Such situation may be explained as it follows:

- The importance of the electric network is increased, and it remain the most critical infrastructure within the hospital;

- The capability of each single infrastructure to autonomously operate has been reduced, due to the need to use the services provided by the others. Obviously, this made the whole system more prone to amplify negative consequences due to cascade phenomena.

To compare the behaviour of the two configurations, we analysed, also, the overall consequences induced by a failure on the IP network (E).

Figure 3.7 shows the behavior in the traditional hospital. The overall levels of inoperability, i.e. the steady state solution of (2), are reported in Figure 3.8.

In such a traditional hospital scenario, it results that that all the infrastructures were only marginally influenced by the failure in the IP-network (E), where only the IT (F) and Bio-Medical apparatus monitoring (H) infrastructures shown a degradation greater than 1%.

The estimated consequences of the same failure, in the modern hospital, were more relevant, as shown in Figure 3.9 (see Figure 3.10).

Simulations shown, for this last case, an increment of the final IP-network inoperability (due to feedback loops) and, also, a generalised diffusion of inoperabilities. Indeed, except for Water (A), Medical Gas (B) and Electricity (L), all the infrastructures shown inoperability levels greater than the 1%. The highest rate of inoperability is shown by the Electronic case history infrastructure (G). It reaches the overall degradation of about 12%. Looking at the Figure 3.6, it is possible to recognise that the direct influence of the IP-network (E) on the electronic case history (G) is $0,63$. Then, neglecting interdependency phenomena, we should have predicted a degradation of about 6%. Nevertheless, the presence of several interdependencies amplify

Stefano De Porcellinis

Hospital Infrastructures	*Steady state level of inoperability*
A – water	0,09%
B – medical gas	0,04%
C – air conditioning	0,03%
D – telephone	0,04%
E – IP network	10,29%
F – IT infrastructures	2,60%
G – paper-based case history	0,001%
H – bio-medical apparatus monitoring	1,23%
I – medical alarms	0,59%
L – electric network	0,02%
M – infrastructures monitoring	0,31%

Figure 3.8: Steady-state level of inoperability associated with the different infrastructures for a traditional hospital in the presence of a failure of 10% in IP-network.

Stefano De Porcellinis

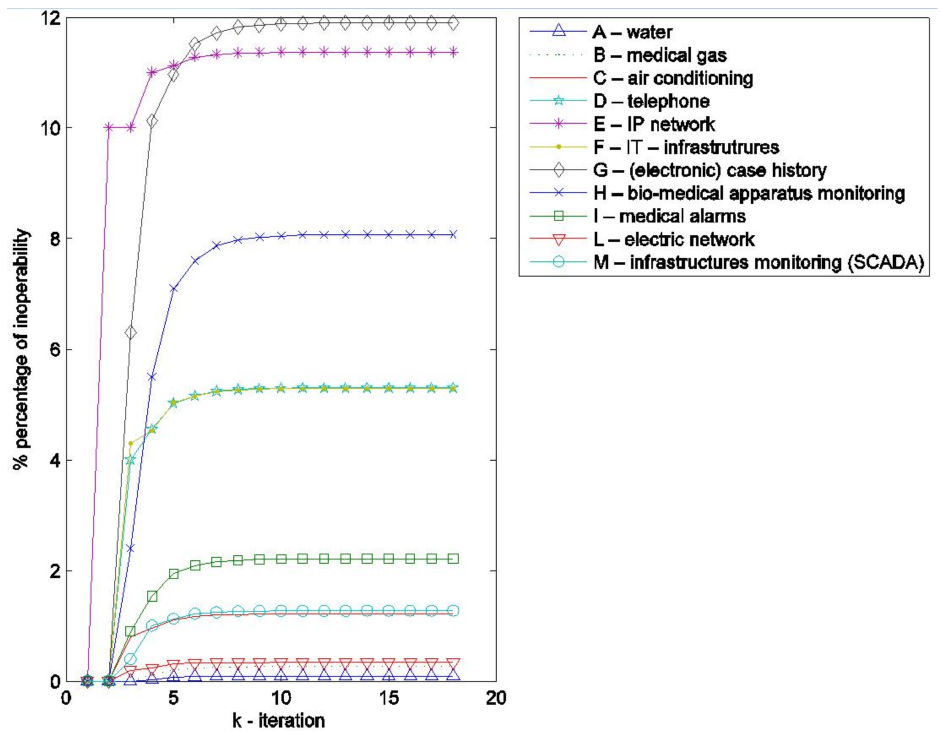


Figure 3.9: Impact scenario induced by a failure that reduces of 10% the operability of the IP-network (E) in a modern hospital. Notice that quite all the infrastructures show a significant degradation and the worst condition is that of the electronic case history system (G) that is affected by an inoperability of about 12%.

Stefano De Porcellinis

Hospital Infrastructures	*Steady state level of inoperability*
A – water	0,09%
B – medical gas	0,27%
C – air conditioning	1,22%
D – telephone	5,30%
E – IP network	11,37%
F – IT infrastructure	5,29%
G – electronic case history	11,89%
H – bio-medical apparatus monitoring	8,06%
I – medical alarms	2,21%
L – electric network	0,34%
M – infrastructures monitoring (SCADA)	1,27%

Figure 3.10: Steady-state level of inoperability associated with the different infrastructures for a modern hospital in the presence of a failure of 10% in IP-network.

the consequences of the original failure, producing a quite double inoperability level.

Obviously, due to the importance (and thanks to technological improvements) of the different infrastructures within modern hospital, they are designed, conducted and managed with higher standards, in order to improve their efficiency, robustness and the business continuity.

Then, the probability that the same "event" might cause similar consequences in both the scenarios is very low. In the every–day activity we observe that, almost all the effects of negative events which affect, as in our example, IP-networks, are absorbed without any appreciable degradation thanks to redundancy of the apparatuses and the back-up elements. However, as our analysis (and several real episodes) shown, if a negative event is able to induce tangible degradations into a single infrastructure, it can be amplified, due to interdependencies and domino effects, up to a level which induces very serious inoperabilities in the whole system.

3.3 Higher order interactions

The indices (3.2) and (3.3) represent, respectively, a measurement of the resilience of the corresponding infrastructure and the influence that a given infrastructure exercises on the whole system. However, these indexes are referred only to the direct influences determined (or suffered) by each infrastructure on the others. Such indexes do not take into account the consequences of the second or higher order of interdependency phenomena, i.e. the effects induced by multi-step cascade phenomena. These overall effects can be then evaluated considering the steady-state solution of (3.1), i.e.

$$\overline{\mathbf{x}} = (\mathbf{I} - \mathbf{A})^{-1}\, \mathbf{c} = \mathbf{S}\ \mathbf{c} \tag{3.6}$$

where $\mathbf{I} \in R^{n \times n}$ is the identity matrix of order n and we labelled by S the matrix $(\mathbf{I} - \mathbf{A})^{-1}$.

Obviously, equation (3.6) holds only when the system (3.1) is stable, otherwise the state variables may grow indefinitely and system (3.1) does not admit any steady-state solution. From the theory of positive system, the system (3.1) is stable *if and only if* the maximum eigenvalue λ_0 of the matrix $\mathbf{A}$ is, in module, less than 1. The Frobenius-Perron theorem guarantees that, in our case, λ_0 is always real and positive and bounded by

$$\max\left(\min_i \delta_i, \min_j \rho_j\right) \le \lambda_0 \le \min\left(\max_i \delta_i, \max_j \rho_j\right) \qquad \forall \quad i,j \in [1,\ldots,n] \tag{3.7}$$

Notice that the meaning of the elements s_{ij} of the matrix $\mathbf{S}$, defined in (3.6), is different from the meaning given to the elements a_{ij} of the matrix $\mathbf{A}$. Indeed, s_{ii} represents the overall inoperability gain in the i-th infrastructure, i.e. the term s_{ii} represents how much the effect of a failure occurred in the i-th infrastructure is amplified due to the presence of interdependencies. On the other side, the term s_{ij} represents the overall inoperability transmission factor from infrastructure j to infrastructure i, i.e. how much of the inoperability injected in the system via the external failure c_j is transmitted to the i-th infrastructure taking into account first, second and higher order of interdependencies.

In the absence of recovery mechanisms, $s_{ii} \ge 1 \ \forall \ i$ (the equality holds only in the case that the i-th infrastructure is completely autonomous) and $s_{ij} \ge a_{ij} \ \forall \, i,j$. In other terms, the presence of the interdependencies amplifies the negative effects on the system. To prove this, we can use the follow result about the stable positive systems

$$\mathbf{S} = [\mathbf{I} - \mathbf{A}]^{-1} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots \tag{3.8}$$

The previous equation emphasises that, the overall inoperability transmission factor is obtained summing to the matrix $\mathbf{A}$, which represents the first order dependency. The terms $\mathbf{A}^2$, $\mathbf{A}^3$, etc. represent, therefore, the second, third and subsequent orders of interdependency.

Notice that, generally, the stakeholders of the different infrastructures have a perception of how much their infrastructure depends on the service directly provided by the other infrastructures, i.e. their first order dependency. Instead, they have very limited information about which could be the implications of higher order interdependencies.

Hence, it results very interesting to us, to stress the contribution given by such higher interdepency orders. This was done considering the relative increment, i.e.

$$\Delta_{ij} = \begin{cases} \frac{s_{ij}-a_{ij}}{s_{ij}} & \text{when} \quad i \neq j \\ \frac{s_{ij}-1}{s_{ij}} & \text{when} \quad i = j \end{cases} \tag{3.9}$$

that represents the amount of the inoperability transmission factor due to the high order interdependencies. A large value for Δ_{ij} emphasizes that the effect of the high order interdependencies is more relevant than the effects deriving only from the direct dependencies. Notice that, such a result, may play a very important role in the definition of the business continuity strategies.

Analogously to (3.2) and (3.3) we considered, also, the *overall dependency index* and the *overall influence gain* defined, respectively, as

$$\overline{\delta}_i = \frac{1}{n-1} \sum_{j \neq i} s_{ij} \qquad \text{(row summation)} \tag{3.10}$$

and

$$\overline{\rho}_j = \frac{1}{n-1} \sum_{i \neq j} s_{ij} \qquad \text{(column summation)} \tag{3.11}$$

These indexes represent, in this case, the estimation for the resilience of the corresponding infrastructure and the influence that a given infrastructure exerts on the whole system, considering both the first and the higher interdependency orders.

Moreover, the comparison among $\overline{\delta}_i$ and δ_i (respectively, $\overline{\rho}_i$ and ρ_i) gives interesting information about the possible amplification deriving from the cascade effect.

Notice that, as I will show in the next section, the dependency degree of all the infrastructures increases with the outage time (as intuitive). Less intuitive there is the fact that, the relative influence exerted by each infrastructure may vary with the tine. This implies, hence, that the infrastructures which result as the most relevant ones during short time outages and during longer time outages are *not always* the same.

3.3.1 Case study

In order to apply such extension of the IIM methodology, we extended the dataset used in Section 3.2.2 with new questionnaires and a different data encoding procedures.
For the new exercise we have taken into account the full set of dependency parameters retrieved during the past exercises for all the 11 different infrastructures. As in the case presented in Section 3.1.1, we collected such a data through 54 questionnaires, each one supplied by a domain expert. At the end of the data collection process, the indexes provided by the experts were codified via FNs and merged as described in Appendix 5.4. Then the entries of the matrices $\mathbf{A}$ have been evaluated using the center of weight rule, in order to extract the crisp values associated with the corresponding FNs.

Hence, we obtained five 11×11 matrices representing the first order influences for the different time intervals that were considered (Table 3.7 reports those related to an outage period of 6h-12h).

3.3.2 Results

Looking to Table 3.7 it is evident that, with respect to an outage time of 6h–12h, the highest influence is experienced by the *Fuel & Petroleum grid* with respect to the *Electricity* with a value of $a(9, 2) = 0.5$. However, the most dependent infrastructure, i.e. the most vulnerable to cascade effect, is the *Air transportation* which shows a *Dependency Index* $\delta_1 = 0.131$. This means that it depends considerable on the services provide by several infrastructures. All the others infrastructures are more resilient with the partial exception of the *Fuel & Petroleum grid* which has $\delta_9 = 0.078$.

The infrastructure least sensible to cascade effects is the *Satellite Communication & Positioning* infrastructure which is independent, as reported by the satellite's experts at least for an outage less than 48 hours, by the services provided by the other infrastructure (then the index δ_{11} is zero). On the other side, this infrastructure is able to exert some influence on the other infrastructures as shown by the *Influence Gain* ρ_{11} equal to 0.038. However the infrastructure which high degree of influence is the *Electricity* with $\rho_2 = 0.127$ follow by the *TLC wired* with $\rho_3 = 0.091$, while the others have smaller values.

It is interesting to analyse how these considerations change considering a different outage time interval. To this end, in Figures 3.11 and 3.12 we report synthetically the evolution of the *Dependency Index* and *Influence gain* for the different outage intervals considered.

It is evident from these figures that, as the outage period grow, the consequences are more serious. Indeed, both the *Influence Gains* and the *Dependency Indices* augment almost monotonically. Notice, for example, that with reference to an outage of 24h–48h the highest value of the matrix $\mathbf{A}$ grows up to the value 0.667 of the entry $a(7,3)$ that represents the impact of the *TLC wired* on the *Finance* system. The fact that the highest value in the matrix $\mathbf{A}$ is assumed by different entries when one consider different time slot emphasize, as mentioned before, that the importance (and the vulnerability) of each infrastructure changes when we consider a different outage period.

This effect is shown by the plots of the *Influence Gains* in Figure 3.12 where, further to the monothonic increment of the values assumed by the *Electricity*, *TLC wired*, and *TLC wireless*, the relative importance of the other infrastructures changes with the time (the curves do intersect each others).

This phenomena is even more evident looking at the *Dependency Index* in the Figure 3.11. There it possible to observe that, for an outage shorter than 12h, the most vulnerable infrastructure is the *Air Transportation* system, while, when the outage overcomes 12 hours, the most vulnerable infrastructure becomes the *Fuel & Petroleum grid*, with an appreciable increment of the vulnerabilities also of *Naval ports* and *Finance*. Such a rapid increment, observed for those infrastructures, could be explained hypothesizing that they use buffering strategies which are dimensioned for short time outages, able to minimize the impact of short–term service outages. However, when the buffers go exhausted, there is a rapid degradation of the operability of the unsupplied infrastructures.

This aspect is even more evident when looking at Figure 3.13, which compares the relative importance of the Dependency Indexes with respect to each outage perdiod.

However, such considerations refer to the dependencies of the first order. In order to consider also higher order dependency phenomena, we need to evaluate the steady state solution of (3.1) that, being in our case-study the matrix $\mathbf{A}$ stable, can be evaluated as (3.6). Table 3.7 reports the case for an outage of 6h–12h.

It is possible to observe that the entries of this matrix are greater than the corresponding one in Table 3.1, and that the entries on the main diagonal are greater than 1 (except for the *Satellite Communication & Positioning* which, being independent from the other infrastructures, is equal to 1). Specifically, the largest entry on the main diagonal is $s(2,2) = 1.012$, a value that underlines how, due to interdependencies, the effect induced on the *Electricity* by a negative event gets amplified by the 1.2% with respect to the original value.

However, as foreseen also by the plots of Figure 3.11 and 3.12, when the outages hold for a long time periods, their effects result more and more relevant. Indeed, for the outage period 24h–48h, we can observe that $s(8,8) = 1,284$ and $s(9,9) = 1,340$, which underline an increment of the "self-degradation" of about 28.4% and 34% for, respectively, the *Naval Ports* and *Fuel & petroleum grid*.

A comparative analysis of the values reported in Table 3.1 and 3.8 allows to identify which elements more dramatically growth when one considers also the high-order interdependencies. This is an important issue because it provide useful information to the infrastructures' stakeholder about the global dependencies existing, for a given scenario, from "his" infrastructures and the services provided by the others, hence allow to better dimensioning buffer elements and contingency polices. For example, comparing the matrices for the 6h–12h case, it is worth to notice how the dependency of the *Fuel & Petroleum Grid* increases its dependency from *Satellite Communication* more than 50% and begins to show a moderate dependency (≈10%) from the *Natural Gas* infrastructure which did not exist in the direct dependencies matrix.

Comparing the values assumed by the *Influence Gain* of Figure 3.12 with those of the *Overall Influence gain* $\overline{\rho}_j$ of Figure 3.15, it was possible to observe that, some infrastructures, like the *Electricity* and the *TLC wired*, doubled their values while, even with a smaller values, the *Natural Gas* infrastructure was characterized by a dramatic growth of its influence, close to the 550%.

Some infrastructures, like *Fuel & Petroleum Grid* and *Transports* show at the steady-state an *Overall Dependency Indices* 3 times greater than the corresponding *Dependency indices* stressing the large impact that the high-order dependencies have for these infrastructures.

Stefano De Porcellinis

Table 3.7: IIM matrix **A** for the time slot 6h-12h (the matrix has been extended with the *dependency index* δ_i and the *influence gain* ρ_j)

	Air transport	Electricity	TLC wired	TLC wireless	Water	Rail transp.	Finance	Naval	Fuel	Gas	Sat. Comm.	δ_i
Air transportation	0.000	0.134	0.456	0.308	0.033	0.024	0.012	0.001	0.024	0.007	0.310	0.131
Electricity	0.000	0.000	0.023	0.010	0.001	0.003	0.000	0.008	0.002	0.178	0.004	0.023
TLC (wired)	0.006	0.083	0.000	0.013	0.004	0.003	0.004	0.002	0.001	0.004	0.005	0.013
TLC (wireless)	0.002	0.109	0.120	0.000	0.002	0.005	0.002	0.002	0.002	0.004	0.007	0.025
Water management	0.005	0.050	0.020	0.009	0.000	0.005	0.008	0.005	0.008	0.008	0.020	0.014
Rail Transportation	0.001	0.233	0.109	0.104	0.005	0.000	0.007	0.002	0.006	0.001	0.004	0.047
Finance	0.003	0.100	0.100	0.030	0.007	0.003	0.000	0.003	0.003	0.007	0.008	0.023
Naval Ports	0.005	0.030	0.020	0.020	0.030	0.030	0.020	0.000	0.010	0.020	0.005	0.019
Fuel & Petroleum grid	0.008	0.500	0.050	0.100	0.050	0.020	0.020	0.020	0.000	0.000	0.008	0.078
Natural Gas	0.002	0.030	0.005	0.009	0.005	0.000	0.002	0.005	0.005	0.000	0.005	0.007
Satellite Communication & Positioning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ρ_j	0.003	0.127	0.091	0.060	0.014	0.009	0.007	0.005	0.006	0.023	0.038	

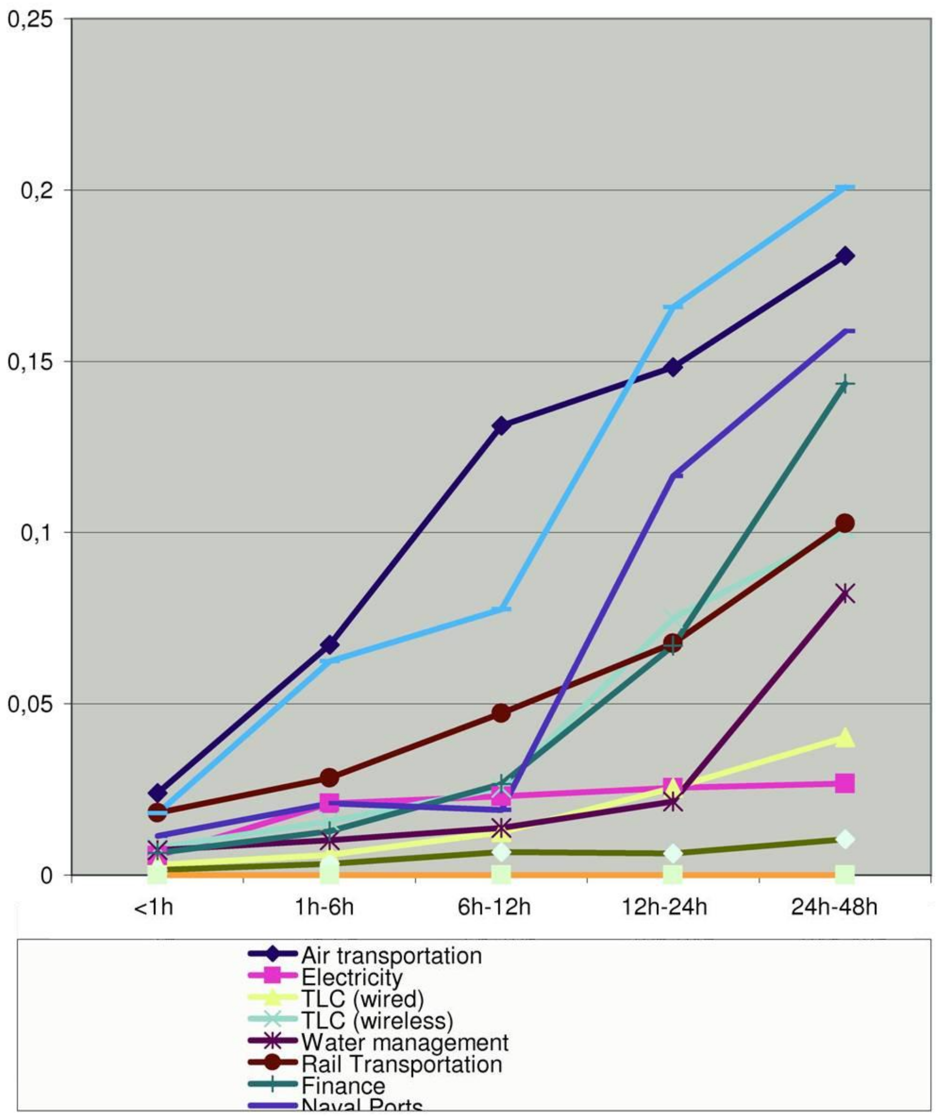


Figure 3.11: Dependency Indexes δ_i for the different outage time

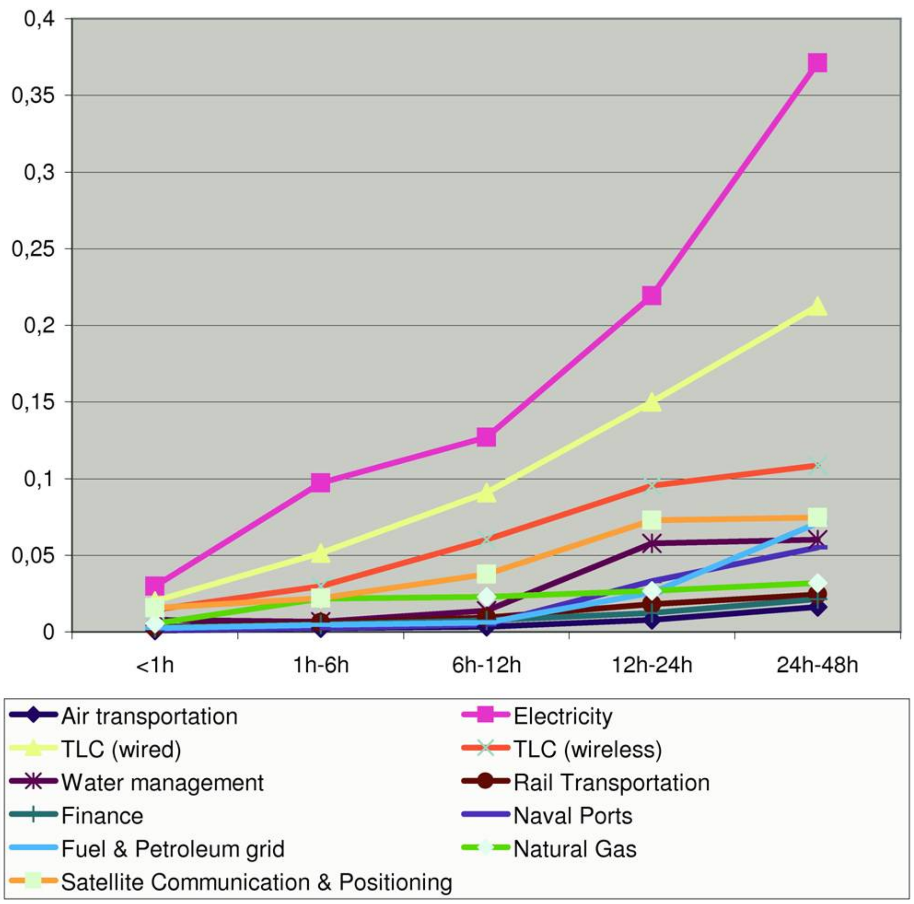


Figure 3.12: Influence Gain ρ_j for the different outage time

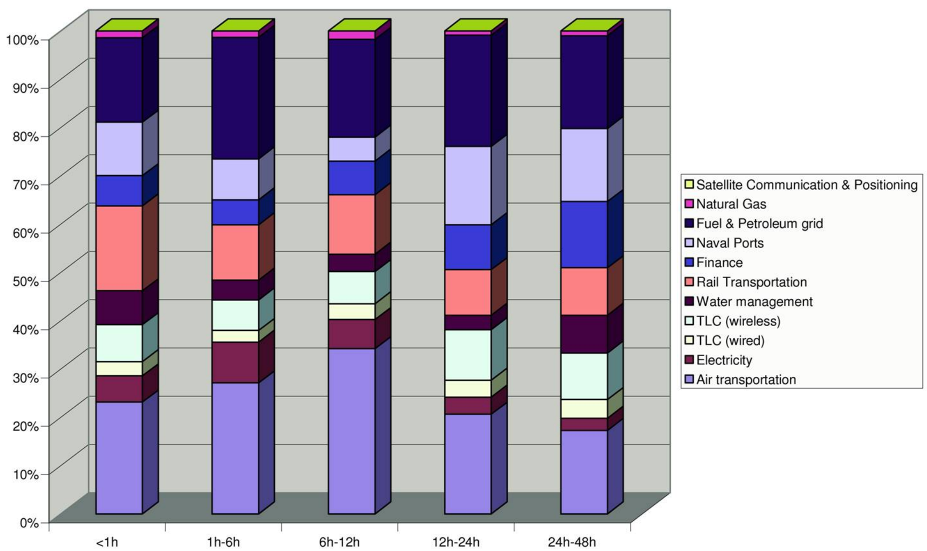


Figure 3.13: Normalised Dependency Index.

Table 3.8: Steady state regime matrix, i.e. $\mathbf{S} = (\mathbf{I} - \mathbf{A})^{-1}$ for the time slot 6h–12h (the matrix has been extended with the *overall dependency index* $\overline{\delta}_i$ and the *overall influence gain* $\overline{\rho}_j$)

	Air transport	Electricity	TLC wired	TLC wireless	Water	Rail trasnp.	Finance	Naval	Fuel	Gas	Sat. Comm.	$\overline{\delta}_i$
Air transportation	1.004	0.238	0.513	0.325	0.038	0.029	0.015	0.006	0.027	0.053	0.319	0.319
Electricity	0.001	1.012	0.027	0.013	0.003	0.003	0.001	0.009	0.003	0.181	0.006	0.319
TLC (wired)	0.006	0.089	1.008	0.017	0.004	0.004	0.005	0.003	0.002	0.020	0.008	0.319
TLC (wireless)	0.003	0.125	0.127	1.005	0.003	0.006	0.003	0.003	0.003	0.027	0.009	0.319
Water management	0.005	0.062	0.028	0.014	1.001	0.006	0.009	0.006	0.009	0.019	0.022	0.319
Rail Transportation	0.002	0.264	0.132	0.111	0.007	1.002	0.009	0.005	0.007	0.050	0.008	0.319
Finance	0.004	0.118	0.110	0.035	0.009	0.005	1.001	0.005	0.004	0.030	0.011	0.319
Naval Ports	0.006	0.054	0.034	0.028	0.032	0.031	0.021	1.001	0.011	0.030	0.008	0.319
Fuel & Petroleum grid	0.009	0.537	0.088	0.115	0.053	0.024	0.022	0.026	1.003	0.098	0.016	0.319
Natural Gas	0.002	0.036	0.009	0.011	0.006	0.001	0.002	0.005	0.005	1.007	0.006	0.319
Satellite Communication & Positioning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.319
$\overline{\rho}_j$	0.042	1.535	1.075	0.674	0.156	0.110	0.087	0.070	0.074	0.515	0.415	

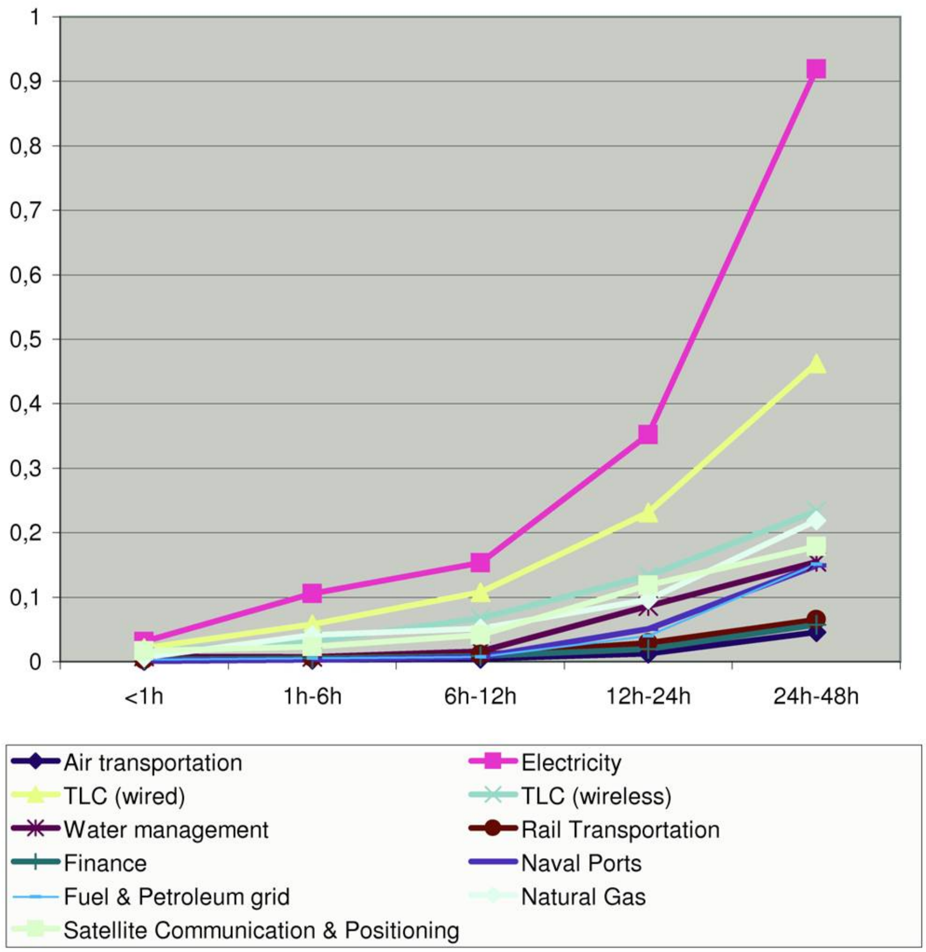


Figure 3.14: Influence gain at the steady-state $\overline{\rho}_j$

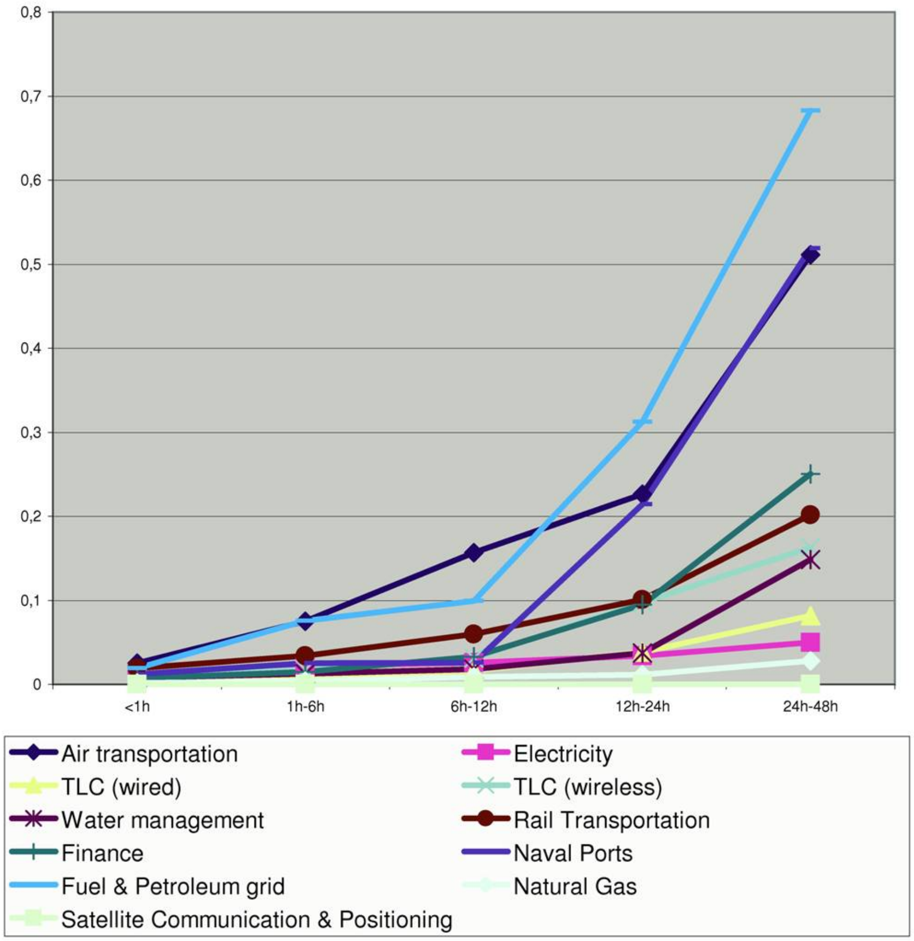


Figure 3.15: Dependency indexes at the steady-state $\overline{\delta}_i$

Chapter 4

Reductionistic Approaches, CISIA

IIM and other holisistic models may enable to perform what is commonly known as *Global analysis*. *Global Analysis*, includes qualitative techniques which help to identify and catalog the different critical infrastructures, and to emphasize the role played by each of them in the global framework. This class encompasses qualitative approaches used to identify infrastructures that are critical, and to single out the role played by each of them into the global framework (e.g., at regional, national or international level). The information needed to set up these "models" are often of linguistic type and may be quite easily collected via expert interviews, round-tables or workshops, and with the help of suitable questionnaires. These methods are very attractive to emphasize macro scale consequences of interdependencies, allowing stakeholders and experts from different areas to share a common framework. Unfortunately, due to the coarse granularity and to the fully qualitative nature, they appear unsuitable to support the definition of operative plans and to improve the reliability of the overall system.

However, as stressed in [S. Rinaldi, J. Peerenboom, T. Kelly, 2001], interdependencies should be analysed with respect to different dimensions. In particular, the authors emphasise that we have to consider al least four not mutually exclusive classes of interdependencies:

- *Physical Interdependency.* Two infrastructures are physically interdependent if the operations of one infrastructure depends on the physical output(s) of the other.

- *Cyber Interdependency.* An infrastructure presents a Cyber dependency if its state depends on information transmitted through the information infrastructure.

- *Geographical Interdependency.* A geographic interdependency occurs when elements of multiple infrastructures are in close spatial proximity. In this case, particular events, such as an explosion or a fire in an element of an infrastructure may create a failure in one or more near infrastructures.

- *Logical Interdependency.* Two infrastructures are logically interdependent if the state of each depends on the state of the other via control, regulatory or other mechanisms that cannot be considered physical, geographical or cyber.

4.1 System analysis

To overcome some limits of global analysis techniques and to allow a more detailed description of fault propagation, the use of sophisticated computer simulators has been proposed in different approaches. We refer to them as *System Analysis* techniques.

These techniques are simulation-intensive approaches that are able to discover hidden interdependencies and to generate (more or less precise) crisis scenarios. They are fine grained quantitative approaches, strongly related with computer simulation. So, they need very sophisticated computational architectures and software, whose complexity may obscure the inevitable subjective inputs and assumptions [M. Dunn, I. Wigert, 2004]. Moreover, they suffer, besides from the problem of defining appropriate models, from the difficulties of acquiring large amounts of detailed quantitative information about each infrastructure. Indeed, infrastructures' stakeholders appear generally very reluctant to disclose these type of data that often are regarded as sensitive information [J. Moteff, G. Stevens, 2003].

An example is given by EPOCHS [K. Hopkinson, K. Birman, R. Giovanini, D. Coury, X. Wang, J. Thorp, 2003]. It is a simulator designed to provide high-quality simulations of electric power scenarios while simultaneously modeling the behaviour of real computer networks. Three commercial and widely used simulators have been federated into a message-broker framework. In particular, EPOCHS integrates the electromagnetic transient simulator PSCAD/EMTCD, which provides detailed simulations of power systems, the electromechanical transient simulation engine PSLF, used by energy industries to simulate real-world situations, and the communication simulator Network Simulator 2 (NS2). NS2 is the most widely used simulator for communication networks based on Internet standard protocols (e.g., TCP/IP). Each of these simulators is considered as an agent that interacts with the others, exchanging results through a proxy agent providing a time scheduling to the whole simulator.

However, the most visionary project on the topic is under development at the NISAC (National Infrastructures Simulation and Analysis Centre). This centre, constituted by the Los Alamos, Sandia and Argonne Laboratories, aims to model and simulate all the infrastructures that are critical for the US with their interdependencies. To this end, NISAC is developing different suites composed by interoperable modules able to support very detailed analysis. Unfortunately, only limited information about NISAC activities are freely available.

4.1.1 Guidelines for the simulator design

In 1998, the Australian Parliament released a report entitled *Thinking about the Unthinkable: Australian Vulnerabilities to High-Tech Risks*. The expression "Thinking the Unthinkable" has become very common in the critical infrastructures community to indicate the huge quantities of unusual, unknown and hidden elements that we have to take into account during the analysis of these infrastructures.

It is evident that setting up simulators as those proposed by NISAC is a very hard task if compared with the effort needed to build a "global approach" model. Information obtainable from first kind of simulators allow to better support the design of operative protection strategies. On the other side, they are less simple, even if more effective, then "global approaches".

Trying to conjugate the positive aspects of the two classes of approaches, we propose an approach which can be considered borderline between the two classes.

Our approach is based on a simulation but, to facilitate information gathering, technical and specific (perhaps sensitive) data are kept to a minimum; the goal is to use coarse grain information obtained by interviewing managers, and to describe internal mechanisms and processes of each element using an adequate level of abstraction. More precisely, we centred our efforts on the definition of a methodology able to model logical characteristics of different and heterogeneous infrastructures, with a manageable level of detail such to capture the most important phenomena but, at the same time, without the need to acquire too much (sensible) information.

From the previous considerations, we derived some desirable characteristics for the simulator, taking also into account that only a limited amount resources is available, both in terms of computing power and software complexity, and in terms of available or elicitable information.

- Each infrastructure is modeled starting from its macro-components, i.e., objects with specific and easily recognizable role, and the global behaviour is figured out from their interactions.

- To reduce the need for detailed information, each element is defined with a sufficiently high level of abstraction that permits consistent descriptions starting from the incomplete and generic data acquirable from stakeholders and open documents. This is also instrumental for the next point.

- The external representation of all the elements (of the same or of different infrastructures) are kept as uniform as possible to ease the descriptions of the networks and coding.

- Knowledge from experts of different fields can be independently elicited. For example, the connections are grouped by their nature in sets that are a refinement of those introduced in the previous paragraph.

- Fuzzy numbers (FNs) are used to code parameters and values in the simulations. In this way, it is possible to represent vague statements as "component B depend very much on component A" and the results of a simulation can be analysed also in terms of their reliability. Fuzzy numbers can be seen as the most natural way to introduce model and data uncertainty in a technical talk. Actually, they represent our believe in a given assertion and are more flexible to use the "a priori" probability. A complete analysis of the relation between probability and fuzzy measures can be found in [D. Dubois, H. Prade, 1998] or in the Appendix A of [T.J. Ross, 2004].

- The description of the blocks are inspired to separateness and self-containment: their behaviours must depend only on values explicitly exchanged with other blocks.

- The simulator imposes no limitation to the kind of representable behaviours so that the experts are free to use the most suitable descriptions of the blocks. Also the dimension of the described system is free (e.g. from a UPS to a nuclear generation plant), it will be chosen according with the scale of the considered scenario and the opinions of the experts.

These considerations suggest an approach to capture the most significant behaviours related with CIP topics starting from fragmented, inhomogeneous and ambiguous information. To this end we decompose each infrastructure into its macro-components to have a "lumped" model composed by n elements, where n depends on spatial/temporal scale and on the level of details required.

Each of these macro-components is characterised in terms of its capability to correctly perform its own task (i.e., to produce a given amount of goods or services) and on its level of failure (actually we consider that each macro-component may be affected by different types of failures each of them with an arbitrary level of severity).

Because we are interested in analysing the system during a crisis scenario, we neglect any internal physical dynamic (that we suppose to be adequate in normal situations) and adopt an abstract description of macro-components' behaviour based on information related to resource availability and failures level. In this framework, we can easily model interactions among macro-components by the exchange of a small and common set of quantities representing the different types of resources and failures considered. Notice that we have to consider multiple types of failures because, as explained in the next section, failure type greatly influences the mechanism of spreading and the impact on the different macro-components.

Then the scenario is described by means of n macro-components belonging to q different infrastructures which exchanges p types of resources and m types of failures. For each of type of resource or failure we have to consider peculiar mechanisms for diffusion that we model, as better explained later, via specific incidence matrices.

4.1.2 CISIA

Using the previous consideration we have set-up a simulation framework, named CISIA (Critical Infrastructure by Interdependent Agents), to analyse failure propagation and performance degradation analysis in a system composed by different, heterogeneous and interdependent infrastructures.

In CISIA each macro-component is modeled with a high level of abstraction and, to reach an acceptable level of modularity and scalability, it is self-contained. Then its input-output behaviour is independent from the state of its neighbours, and it is based only on the quantities exchanged with them. In other words, each element has no (explicit or implicit) information about which are its neighbours neither about their state or internal model.

Macro-component dynamics

Each Macro-component is modelled as an autonomous block (in the following called "entity") whose behaviour is described, at least, by the following quantities:

- *Operative Level* (OL): represents the capability of the entity to perform its job. It represents only the potential capability, in the sense that an *Operative Level* of 100% does not mean that the system is working at its maximum capacity, but that it could if required. This quantity dynamically varies during time in the range [0, 1], and any abnormal situations is identified by its reduction from the unit. It is represented by a FN.

- *Failures* (F): is a structured variable which enumerates the types of internal failure that can affect the entity. It also stores the associated levels of severity. While the types of failure are static properties of the entity, the associated levels of severity can dynamically increase (they cannot decrease we exclude fixing procedures from the simulation).

Failure severity is normalised in the range [0, 1], where 0 represents the absence of failure and 1 its maximum possible amount. Some failures are binary quantities, but other are represented via FNs which allow to discriminate from *very small* to *disastrous* failures.

Each entity is characterised also by a set of constant quantities used to better specify its behaviour. Among others we cite: *Requirements* (REQ) and *Nominal Production Level* (NPL) which specify types, unit of measurements, and nominal value of *Resources*, respectively, needed to reach or produced when $OL = 100\%$.

Entities interact only via the exchange of the following quantities:

- *Resources* (R): goods and services produced (or used) by the entity expressed in terms of their types, unit of measurements, nominal values and actual levels. Notice that, as for the OL, *Resources* do not represent the effective amount of goods produced (used), but the maximum affordable quantity that the entity could produce (use) if required. It is assumed that the i-th entity produces and uses, respectively, p_i and r_i different types of resources (where number and types depend on the characteristic of the entity).

- *Consumption* (C): resources effectively used by the entity expressed in terms of their types, unit of measurements, nominal values and amount. These quantities are fed-back to producers where they are used to estimate the overall consumption in order to check for saturation effects or overload conditions.

- *Failures* (F): failures propagated from (or to) the entity expressed in terms of their types and the associated levels of severity. It is assumed that the i-th entity is affected by m_i different types of failures (where number and types depend on the characteristic of the entity).

Specifically entity's input and output are:

R_{IN}	Resources used by the entity
C_{IN}	Amount of resources actually required by downstream elements
F_{OUT}	Failures propagated to the entity
R_{OUT}	Maximum resources that the entity can produce if needed
C_{OUT}	Actual amount of resources consumed by the entity
F_{OUT}	Failures propagated from the entity to other elements

We base entities's interactions on exchange of *Resources*, instead of actual productions, to improve simulation efficiency reducing the presence of loops. Indeed, even if we adopt a producer-consumer paradigm, the two components are partially decoupled because the consumer operates on potential capability of the producer, which, in turn, is completely independent from consumer requests until consumes do not induce overload.

The *Operative level* of each macro-component is set to 100% if there is no internal failures (F) and the available resources (R_{IN}) are greater or at least equal to the entity requirements (REQ). Otherwise, the entity's *Operative level* is progressively reduced to zero. When OL=0 the entity is not able to supply any resource, but even in this case, it may still generate and/or transmit failures.

Specifically

$$OL_i = \prod_{k=1}^{m_i} \left(\Lambda_k \left(F(k)\right)\right) * \prod_{j=1}^{r_i} \Theta_j \left(\frac{REQ(j)}{R_{IN}(j)}\right) \tag{4.1}$$

where Λ and Θ are functions which assumes values in the range $[0, 1]$. Λ is a decreasing function with $\Lambda_k(0) = 1$, while Θ_j is an increasing one with $\Theta_j(1) = 1$.

Inside CISIA, to allow the modeling of the broadest range of behaviours in a common framework, we allowed these functions belonging to three classes, illustrated in Fig. 4.1, or to weighted combination of them. Notice that, linear (a) and threshold (b) functions are generally more easily to configure, even if better fitting of experimental data are obtained with logistic curves (c).

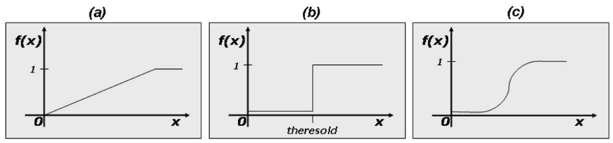


Figure 4.1: Triangular Fuzzy Numbers representation.

The same classes of curves are adopted for all the function used in this section.

The resources produced by the entity is assumed proportional to the *Operative Level* via its *Nominal Production Level*

$$R_{OUT} = OL * NPL \tag{4.2}$$

On the other hand, the entity's consumption depends on the *Operative Level* and on all the requests coming from other elements.

$$C_{OUT} = \Omega\,(OL,\ C_{IN},\ NSL) \tag{4.3}$$

where NSL specifies the *Normal Suppliable Level*, a reference value that represents the amount of resource that the entity can supply with an OL of 100% in a steady state. The previous expression for an entity with a single output, may be specialised as

$$C_{OUT} = OL * \frac{C_{IN}}{R_{OUT}} * NSL \tag{4.4}$$

In the occurrence that the entity receives a failure of type X that it is "supported" by the entity, it updates the correspondent internal state by means of

$$F(X) = \Psi_X \left\{ F(X),\ \Delta \left(F_{IN}(X) \right),\ C_{IN} \right\} \tag{4.5}$$

where Ψ_X is a suitable functions which models how internal failure is influenced by external failures, by overload or other entity-specific causes; Δ represents a suitable function that scales the severity of the input failure in accordance with the entity protection profile.

Internal failures may generate output failure (F_{OUT}) that spread to neighbours entities identified in accordance with the specific concept of proximity.

The vectors R_{OUT}, C_{OUT} and F_{OUT} are passed to the *Transmission Sub System* that, as explained in the next section, decomposes them in *messages* that are sent to the different neighbours.

Dependencies modeling

An important part of the modeling effort was reserved to the representation of the dependencies and interdependencies, being them the cause of the complex behaviours we are interested in. Each macro-component, as anticipated before, interacts with the others via a multitude of mechanisms. Some of them, related to functional dependencies may be assumed quite well known, because they have been conceived and voluntarily built to directly contribute in the normal operations.

Typically, over these functional links, the macro-components distribute the products or the services produced by a component to the downstream ones. Even if some kind of failures may be propagated along such paths, we preferred to use logically distinct links for this kind of connections. Other connections exist, referred to *indirect links* in [R. Benoit, 2004], that, not specifically constructed nor planned, are very often originated by some kind of proximity. Sometimes they do not exist at all in normal conditions and they appear as a consequence of specific failures, or emerge after some changes in the context in which the infrastructures operate.

In the following, to stress their different nature, we will distinguish between *Resources* links, related to quantities directly used by each macro-component to perform its activities, and *Failure propagation* links, used to describe paths along which failures might be propagated.

In both categories we have to consider a multitude of different propagation mechanisms, each one characterised by its own properties, often related to different topologies or metrics. This implies that, for each macro-component, we need to define several sets of different neighbours.

Then, in CISIA, interactions among macro-components are described in terms of sending/receiving messages exploiting the presence of a multitude of *oriented weighted incidence matrices*, each one representing neighbours associated with a given phenomena, e.g., geographic proximity or electric propagation.

The use of different kinds of matrices, beyond the emphasis on different characteristics of each dependency, simplifies interdependencies' discovery. Indeed, considering the taxonomy introduced in [S. Rinaldi, J. Peerenboom, T. Kelly, 2001] physical interdependencies are, generally, well known to infrastructure's experts and could be read from functional schemes. On the other hand, geographical interdependencies are less understood by experts, but they can be discovered comparing infrastructures' maps.

Each entry in these incidence matrices is characterised by two coefficients: one represents attenuation from the source to the destination, and the other represents the time delay needed for its propagation (in the actual version, this is the only 'crisp' quantity).

Moreover, for what concerns failure propagation, our approach distinguishes between spreading and diffusion of a failure. More specifically, any failure is spread to all the members of the corresponding set of neighbours,

Stefano De Porcellinis

but this represents only a necessary condition for the propagation of the fault, i.e., its diffusion. Indeed, we consider also other specific characteristics of the macro-component reached by the fault (e.g. actual state, internal level of failure, presence of adequate protection profiles, etc.) that can reduce the severity or even block the propagation of the failure.

The simulation is primarily constituted by the entities and the adjacency matrices. Entities and matrices are collected in two main structures, respectively Entity Pool (EP) ant Transmission Sub System (TSS), depicted in Fig. 4.2.

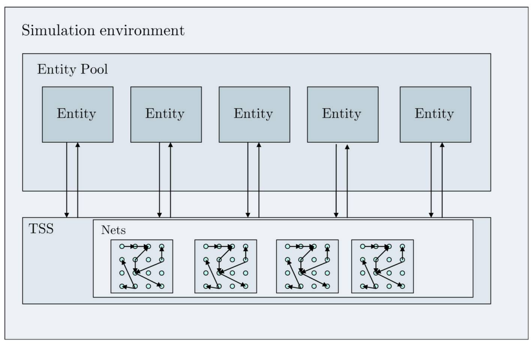


Figure 4.2: The simulator is composed by two main structures: the *Entity Pool* devoted to handle entities's evolution and the *Transmission Sub System* (TSS) that manages communication among entities.

The Transmission Sub System (TSS) is devoted to manage the communication between the entities. Entities communicate via message exchange, where each message contains data about the type and the denormalized quantity of carried resource (or fault), the normalizing factor, the unit of measurement and the sender port ID. When the TSS receives the signal from the simulation clock, it collects the outgoing messages from all the entities and delivers each message to the neighbours of the sender entity, in accordance with the adjacencies described in the matrix associated with the type of the carried quantity. If a link between two adjacent entities is characterized by attenuation or delay factors, TSS provides to delay the delivery of the messages routed over that link and to suitable scale the carried quantities.

4.1.3 Case study

We tested CISIA analysing the possible consequences of a failure inside one of the electric power plants that supply electricity to the area of Rome.

For what concerning our goals, this area can be modelled in a very crude approximation, considering the presence of five logically autonomous macro-components.

- Power plant: that represent electricity production plant located close to the urban area of Rome. This entity models a set of power plants geographically co-located in the same area (which share common resources as fuel storage and water cooling system).

- 380kV substation: this entity represents the point of contact from the local electric network and the national grid. Even if actually the area of Rome has several interconnection points, for our analysis we assumed the presence of a single interconnection point.

- Energy transportation network: Composed by a single grid with the associated tele-communication and control network, able to dispatch electricity to urban areas.

- Urban areas: specifically we consider two close urban areas of different size. The *Big city* represents the town, while the *Small city* is the suburban area where is located the centre that supervises and controls the national power grid and tele-controls the different power plants. Obviously, the actual architecture used to supervise the national power grid is more complex and foresees the presence of different local centres that are coordinated by a national node (this latter replicated in different geographic locations to guarantee high availability and dependability).

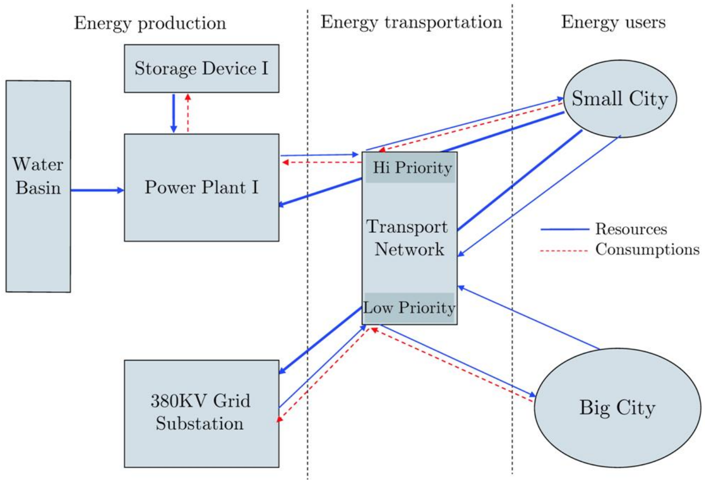


Figure 4.3: The case study scenario: a simplified view of the urban area around Rome and its electricity supply system.

In a very simplified manner, we assume that the power plant needs, in order to generate electricity, fuel from the storage entity, water from the basin entity and control information from the small city entity. Moreover, we assume that electricity consumptions are so high that local generation represents a mandatory component. On the other side, the transportation network receives electricity from the power plant and the 380kV substation supplying it to urban areas. In our scenario the operative level of urban areas is strictly related to the presence of electricity: when a black-out persists for a certain amount of time, there is a degradation in the basic services, and this induces social disorders and insecurity phenomena (i.e., a social fault in the urban area). Moreover, we suppose that electric grid adopts a dispatched policy to priority supply electricity to the small city where is located the control-centre for the power plants.

In our simulation we assume that at the tick $T = 20$ a fire abruptly turns off the fuel storage which supplies the power plant (see Fig. 4.4.a).

Even if the 380kV substation continues to supply electricity (see Fig. 4.5), there is not sufficient power to satisfy the requirements coming from both

Stefano De Porcellinis

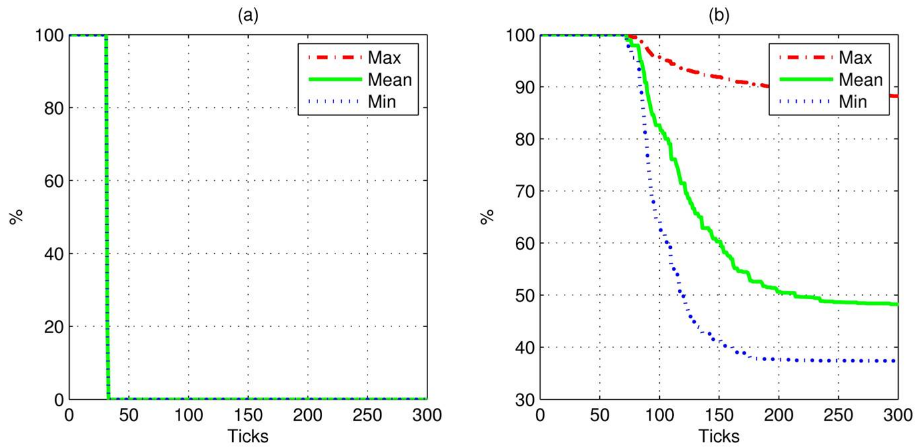


Figure 4.4: Operative Level of the power plant (a) and 380kV substation (b). (All values are FNs)

the urban areas. Then, in accordance to its dispatching policy, the electrical network reduces the amount of power supplied to the big city through the low-priority line (see Fig. 4.6.a). This shortage, after some time, induces problems in the big-city due to the absence of electricity in important services. Therefore the *Operative Level* of the town is reduced (see Fig. 4.7.a).

As evident looking to the simulation results, because we have adopted a triangular FNs representation of the different quantities, the time histories' of these latter are composed by three curves. The middle one (i.e., the solid line) represents the most "believable" behaviour, while the other lines represent, respectively, an estimation of the best and worst case. Moreover, we are able to characterise the evolution of the uncertainties that, for each variable, is proportional to the difference between its maximum (line-dotted line) and minimum (dotted line) values.

Looking to Fig. 4.7.b we note that after some ticks, even if there is no reduction in current supplied to the small city (see Fig. 4.6.b), we record a degradation also in the *Operative Level* of this second urban area.

This behaviour is related to the propagation of the sociological failure gen-

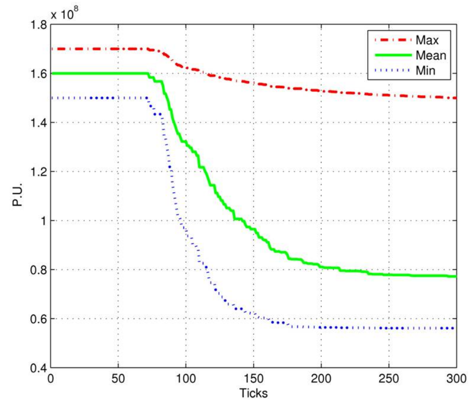


Figure 4.5: Power supplied by the 380kV substation (All values are FNs)

erated inside the big city. Indeed, black-outs produce degradation in critical services (e.g., stop of railway transportation, traffic congestion, difficulties in communication, problems in health-care and emergency services, etc.) and this induces social disorders that in the model are supposed to spread also to the small city due their geographical proximity (see Fig. 4.8.b).

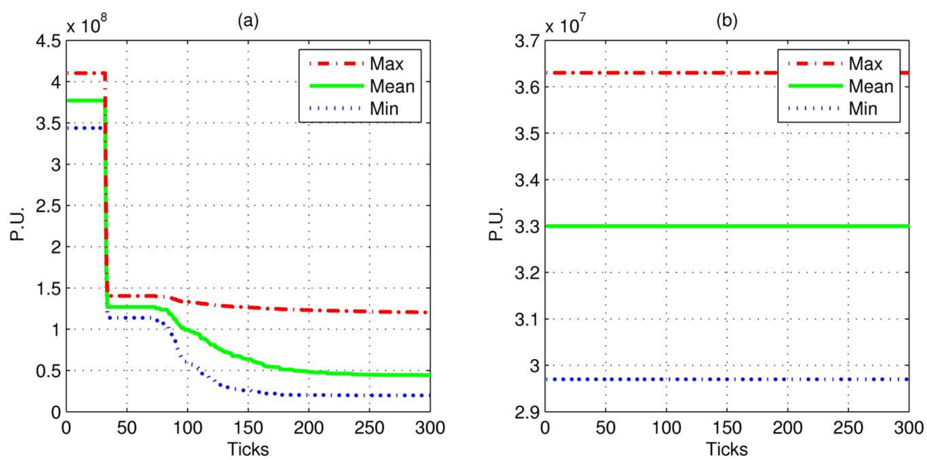


Figure 4.6: Amount of electricity available for the big city (a) and the small city (b). (All values are FNs)

The presence of these disorders has an impact also on the capability of the control centre to efficiently manage national grid, and then the 380kV substation (see Fig. 4.5). This implies that the substation reduces the amount of electricity provided (see Fig. 4.6). This exacerbates the black-outs problems in the big city and, obviously, increases the level of social disorder. These disorders are then spread to the small city where we register further reduction of the operative level, and so on.

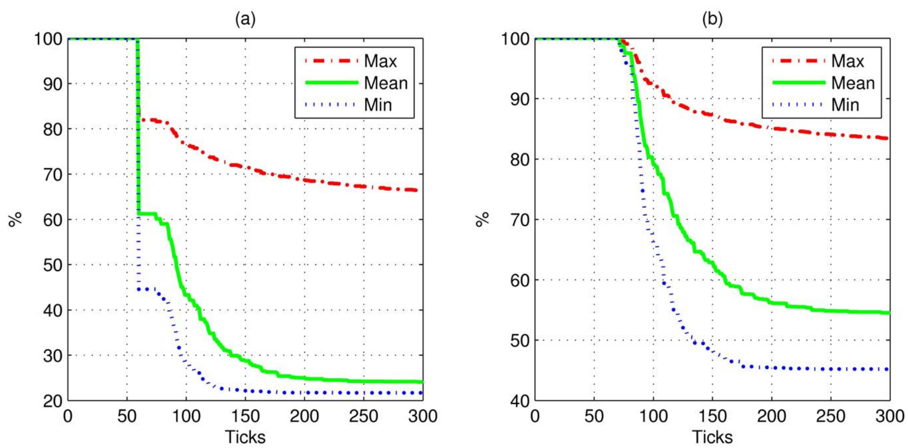


Figure 4.7: Operative Level of the big city (a) and of the small city (b). (All values are FNs)

In steady state we note that, even if the small city is continuously supplied, its operative level is reduced to about the 40% of its nominal level. This emphasizes that, in this very simple scenario, the dispatched policy adopted appears to be partially uneffective and suggest the opportunity to analyse different strategies.

Notice that the reported results have been unrealistically augmented and time compressed to emphasize the consequences of cascade failures.

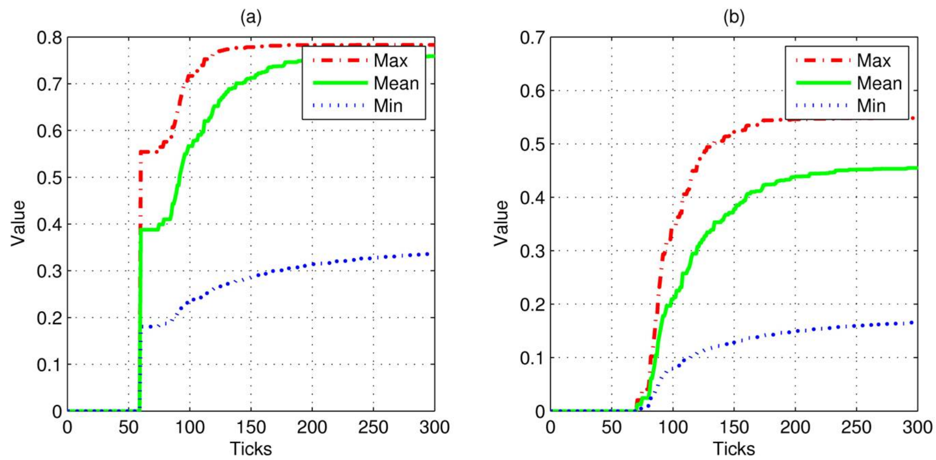


Figure 4.8: Sociological Failure that affects the big city (a) and the small city (b). (All values are FNs)

4.2 Federated simulation of eterogeneus complex systems

4.2.1 Reasons for a federate simulation approach

As appeared from the previous experiences, the primary challenge for our simulation tools was the need to model heterogeneous infrastructures into a common conceptual framework. Another major challenge was to model the interdependencies existing among infrastructures and between infrastructures and the environment. In this context we need to consider at least two different classes of interdependencies: *intra-domain* and *inter-domains*. The former class includes functional links that exist among components belonging to the same infrastructure. Generally this type of relationships are quite well know and strictly related to the specific domain. The latter class, although, includes links which represent functional and not functional relationships among elements belonging to different infrastructures, e.g. the relationships between a computer and an electric substation. Information about inter-domains relationships are generally scarce, in spite of the fundamental role played by those links in the process of interdependency emergence.

Several projects are analysing the power and the limits of "monolithic" approaches, aimed to encompass, within the same framework, all the peculiaties of any infrastructure and the corresponding set of interdependencies[S. De Porcellinis, S. Panzieri, R. Setola, G. Ulivi, 2008, M. Permann, M. Manic, 2006, S. Panzieri, R. Setola, G. Ulivi, 2005, The NISAC (National Infrastructures Simulation and Analysis Centre)]. In the follow we refer to this type of solution as *horizontal simulators*, because they covers multiple domains, and use abstract modeling framework to represent multiple heterogeneous infrastructures. These simulators engage a variety of concepts, structures and solutions, e.g., complex adaptive systems [S. Rinaldi, J. Peerenboom, T. Kelly, 2001], agent-based modeling [E. Casalicchio, E. Galli, S. Tucci, 2007] and entity-relation approaches [S. De Porcellinis, S. Panzieri, R. Setola, G. Ulivi, 2008].

Unfortunately, except for NISAC [The NISAC (National Infrastructures Simulation and Analysis Centre)] and a few other government initiatives, horizontal simulators have been tested only on relatively very simple scenarios. This is primarily due to modeling issues, because it results extremely difficult to acquire detailed information about such infrastructures. Such difficulties do not reside only in the reluctance of, almost all, the stakeholders to provide detailed data. Often, the main difficulty resides in the models formulation, due to the need to translate those datafrom infrastructure domain to the abstract formulation adopted by the horizontal simulators. A different approach, commonly followed, is to federate a set of domain-specific simulators. In such a case, the simulation of the internal behaviour of each infrastructure is delegated to the corresponding domain-specific simulation tool, while the outputs produced by the different simulators are merged togheter, in order to reproduce the interdependency phenomena. An example of such approach is EPOCHS [K. Hopkinson, K. Birman, R. Giovanini, D. Coury,

X. Wang, J. Thorp, 2003], which was designed to analyse interactions between the electric power grid and undelying telecommunications networks. Another example is represented by SimCIP (developed in the framework of the European IRRIIS project [The IRRIIS European Integrated Project]), a simulation environment which was developed with the aim to support the simulation of different scenarios embedding several vertical simulators into a single framework.

Notice that in this way each domain-specific simulator uses an autonomous, e.g. isolated, model of the corresponding infrastructure. They provide a vertical (partial but detailed) view of the infrastructure. For this reason, in the follow we will refer to the domain-specific simulators as *vertical simulators*.

Unfortunately, simple federation of vertical simulators is often unable to capture all the large set of interdependency phenomena present in real-world scenarios. Indeed, as better explained in the following, they are able only to describe interactions between infrastructures in terms of some functional links (e.g., direct exchanges of goods and services), neglecting all the other types of possible interdependencies (e.g., geographical, organizative or social links) [S. Rinaldi, J. Peerenboom, T. Kelly, 2001]. Moreover, because often vertical simulators cannot manage information belonging to other domains, they are able only to reproduce very few elementary mechanisms of inter-domain interactions

To overcome the limitations of these two classes of simulation approaches, a more structured simulation framework was begun to be developed, with the aim of integrating several vertical simulators by means of an horizontal simulation environment. Such a simulation framework (referred in the follow as CRESCO framework) has been developed under the CRESCO Project, which is funded by Italian Ministry of Research to enhance the national capability to study complex systems. However, it is necessary to stress that the framework developed within the CRESCO project was not intended to be the "silver bullet", that comprehensively addresses all the critical infrastructures' simulation problems. Rather, it has to be intended as a proof-of-concept aimed to contribute to the design of a European Infrastructure Simulation and Analysis Center (EISAC).

In the following I will describe the rational behind the CRESCO framework, resulted from jointed effort of many national research centers and institutes (like ENEA, Consorzio CRIAI, Universitá of Rome "Tor Vergata" and Campus Bio-Medico), illustrating how CISIA represented a valuable solution in order to implement the federate simulation environment.

4.2.2 CRESCO modelling approach

The CRESCO framework is characterized by the presence of horizontal simulation environments that are used to integrate a set of vertical simulators.

Classical federated simulation solutions employ a simple mediation gateway that translates and synchronizes inputs and outputs produced by the vertical simulators. CRESCO solution is more sophisticated because it "processes" inside the horizontal simulators the information produced by the vertical simulators, integrating them with further elements that are peculiar to the horizontal framework i.e. that cannot be modelled by vertical simulators due to their intrinsic inter–domain nature.

To explain these differences, we need to better formalise the different approaches. To this end let us indicate the status of the i-th component of the x-infrastructure as x_i, where the status refers to any quantity that describes a characteristic (efficiency, operability, etc.) of the element.

A vertical simulator updates the status of its elements by solving an equation of the form:

$$x_i(k+1) = f_X(X(k), u(k), \bar{P}_{x_i}) \tag{4.6}$$

where $X = [x_1, \ldots, x_n]^T$ represents the status of all the elements that constitute the x-infrastructure, e.g., voltage at each nodes in the case x is an

Stefano De Porcellinis

electric grid. u is the vector of external inputs (e.g., loads), $\bar{P}_{x_i}$ is the set of parameters characterizing the i-th element and $f_X(\cdot)$ is a function that describes the dynamics of the x-infrastructure. The form of the function $f_X(\cdot)$ depends on the nature of the infrastructure and may be expressed via differential equations, algebraic relations, etc. Note that $f_X(\cdot)$ takes explicitly into account intra-domain relationships existing between the elements in the x-infrastructure, i.e., the "physical" constraints that characterise the specific infrastructure (e.g., the Kirchoff laws for an electric network).

If two or more vertical simulators are federated using a simple broker gateway, equation (4.6) is modified to account for the presence of inter-domains interdependencies. For simplicity, we consider the case of just two infrastructures, x and y, and assume that a one-to-one correspondence exists between elements in the two infrastructures (these assumptions can be straightforward relaxed). In this case, equation (4.6) becomes

$$x_i(k+1) = f_X(X(k), u(k) + \delta(y_i), \gamma(\bar{P}_{x_i}, y_i)) \tag{4.7}$$

where δ and γ are functions that translate into input and/or parameters variations the values assumed by the state variable y_i of those element of the y-infrastructure directly connected to x_i. Hence, the federation process corresponds to a fictitious modification of the load u and/or parameters $\bar{P}_{x_i}$, making them dependent on the status assumed by the element of the y-infrastructure that is in direct correspondence with x_i. As mentioned above, this strategy has several drawbacks. In particular, it permits to reproduce only very simple interdependency phenomena.

On the other side, the dynamics of an element in a horizontal simulator is described by:

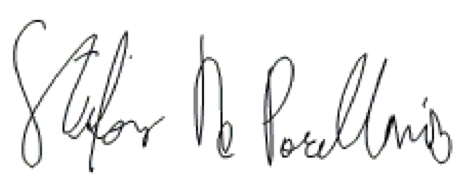
$$\theta_i(k+1) = \Gamma_\theta(\theta_i(k), u(k), M(\Theta)) \tag{4.8}$$

where $\theta_i \in \Re^{n_i}$ is the state of the i-th element, Θ is the vector composed by the state variables of all the elements in the simulation scenario, Γ_θ is a function describing the dynamics of each element and $M(\cdot)$ is a function describing the inter- and intra-domain relationships existing between the i-th element and all the other elements without any specific consideration about the nature of the infrastructure. Note that the horizontal simulation techniques proposed in the literature differ in the methodology used to map interdependencies by means of the function $M(\cdot)$ and in the formalism adopted for their representation.

The main difference between equations (4.6) and (4.8) is that $f_X(\cdot)$ depends explicitly on all the variables of the system while Γ_θ depends only on the state variables of the i-th element; this because the influence exerted by the other elements is mediated by $M(\cdot)$, which codifies the relationships between the different elements. Therefore, equation (4.8) provides a less detailed and less coherent representation of intra-domain relationships than equation (4.6). However, it is able to describe inter-domains dependencies better, because it adopts a more general formalism.

We believe that some of the drawbacks of these two approaches can be overcame by integrating several vertical simulators by means of an horizontal simulation framework. This strategy leverages the capabilities of the vertical simulators to correctly reproduce the behaviour of individual infrastructures and the ability of horizontal simulators to model a larger class of inter-domains relationships.

Specifically, with the CRESCO approach the overall state of the i-th element (θ_i) is obtained by incorporating, within the horizontal simulator model, information about the "partial" view of the element obtained by considering the x-, y- infrastructure models. Notice that, the data provided by the vertical simulators are not simple "staked' to compose the θ_i state vector (as done in a federated schema), but used as inputs for the horizontal model, as formally illustrated in equation (4.9). Viceversa, θ_i is used to update the variables of the vertical simulators in order to propagate the consequences of inter-domains phenomena in those vertical environments. Then, there is



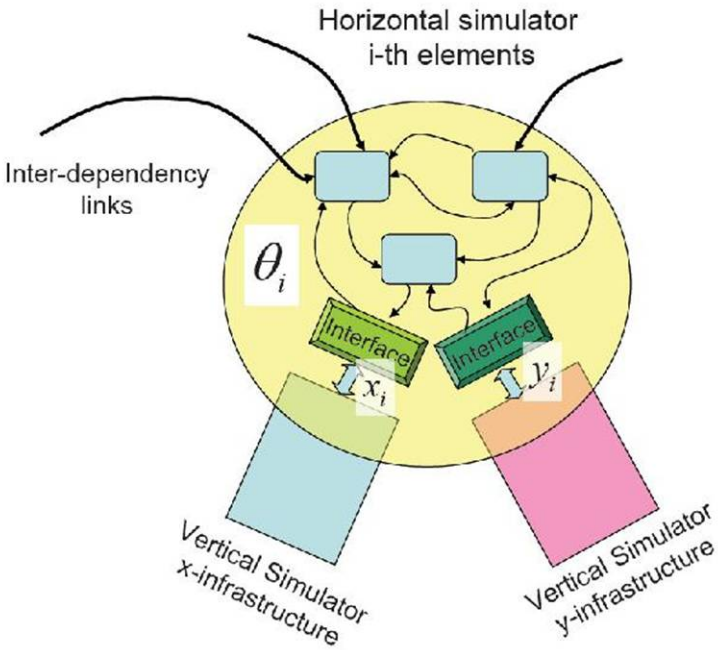


Figure 4.9: Global behaviour of the i-th element

no direct propagation of the outputs of the x–infrastructure' vertical model into the y–infrastructure' vertical model, but this is mediated by means of the horizontal simulator. In this way it is possible to merge information provided by other vertical simulators, in order to manage exceptions and consider further elements and phenomena that, otherwise, could be difficult to include inside the model. The global behaviour of the i-th element, formally we have:

$$\begin{aligned}
\theta_i(k+1) &= \Gamma_\theta(\tilde{\theta}_i(k), u(k) + \delta_\theta u\,(x_i, y_i)\,, \hat{M}(\Theta)) \\
x_i(k+1) &= f_X(\tilde{X}(k), u(k) + \delta u_x(\theta_i), \gamma(\bar{P}_{x_i}, \theta_i)) \\
y_i(k+1) &= f_Y(\tilde{Y}(k), u(k) + \delta u_y(\theta_i), \gamma(\bar{P}_{y_i}, \theta_i))
\end{aligned} \tag{4.9}$$

where $\hat{M}(\cdot)$ is a function that considers only the inter-domains relationships and the tilde ($\tilde{}$) symbol means that the corresponding variable has been

Stefano De Porcellinis

updated with regard to its own (i.e., isolated) value based on data provided by the other simulators.

4.2.3 Horizontal and Vertical models integration

As illustrated before, CISIA adopts a *component-wise* approach. In the spite of the federation aim, we can interpret CISIA componet model as a multi-layer structure (Figure 4.10), where each layer takes into account the fact that the component relies on different infrastructures. For example, a router is modeled as a three layer entity that has its own functioning mechanism, that relies on the communication network and that relies on the power grid and auxiliary power devices. In the federated implementation of CISIA, the evaluation of detailed behaviour associated with each single infrastructure is demanded to domain-specific vertical simulators. Then, information provided by these simulators are merged at component level in order to obtain a "complete" model of each entity, i.e. a model able to integrate the different partial visions provided by the vertical simulators within a behavioural model of the component.

With reference to the formalism of equation (4.8) we have that

$$M(\Theta) \cong \sum_{l} M_l(\Theta) \tag{4.10}$$

where, in this case the vector $\Theta = [\theta_i, \ldots, \theta_n]^T$ and the state of each entity is composed by the entity operative level, and the severity of its internal failures, i.e. $\theta_i = [OL_i, F_i^1, \ldots F_i^{p_i}]$.

The model paradigm adopted by CISIA largely facilitates the integration with vertical simulators. Indeed the outputs of these latter (i.e., x_i and y_i of equation (4.9)) can be logically managed as external resource in equation (4.1). Obviously, there is the need to trans-codify these quantities, in order to fit the more abstract representation adopted in CISIA. This is done by aggregating data using the proper ontology.

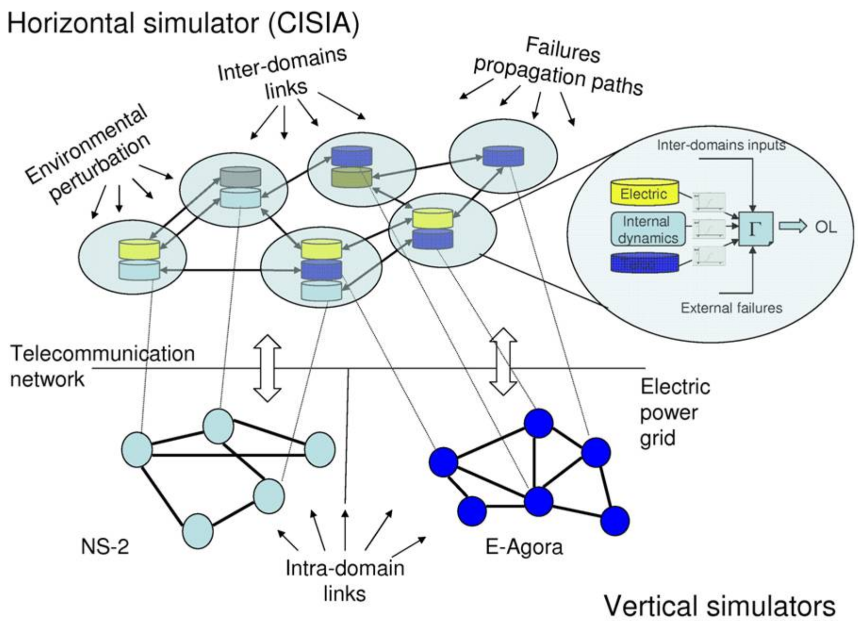


Figure 4.10: The CISIA modeling and simulation approach

More challenging is the information flow from CISIA to the vertical simulators. This is due to the less flexibility that these software packages have being not specifically designed to be integrated with other simulation environments. Moreover, we need to map abstract information, like the Operative Level that characterizes the state in CISIA, into more detailed and tangible quantities as electric power supply or number of packets dropped. This imposes to perform a data decomposition which necessarily introduces some degree of arbitrary. This process is further complicated by the fact that CISIA codifies information in terms of Fuzzy Numbers; while this formulation facilitates the fusion of data provided by vertical simulators, allowing to easily aggregate into the same variable several elementary quantities, it makes more challenging the inverse process. Indeed, in this case one needs to transform fuzzy data into crisp quantities, and implicitly this operation is accomplished by a lost of information.

Stefano De Porcellinis

4.2.4 Case study

The CRESCO environment has been tested with the model paradigm adopted by CISIA, using a real reference scenario. For obviously reasons, in the follow we have anonimised all the references and used fake images. Such a scenario has been selected for its peculiarity to have, in an area of approximately 350 km^2 several heterogeneous and interdependent infrastructures. Indeed, inside such geographical framework there are:

- Several TLC networks, each one composed by both wired and wireless segments
- Very high voltage electrical transmission network (also several generation plants are presented in the area)
- Medium voltage electrical distribution network (together with the correspondent telecontrol framework)
- Two commercial air-ports
- Two medium-to-large commercial sea-ports
- One long-range railway network and one local railway line.
- An highway system
- One major urban area (with more than 300.000 inhabitants) and five minor urban areas

In order to cope with the intrinsic complexity of such a scenario, also due to the difficulty to find detailed information about the numerous components which constitute the different infrastructures, some simplification were introduced in the simulated components, their functional models and interaction policies.

The simulation scenario included about 200 macro–components, belonging to 35 different functional classes and linked with each other through more that 1.700 dependency links.

To limit the complexity of the resulting models, it was decided to define a 36 hours temporal horizon for the longest simulation trial, implementing only the functional dynamics which result compatible with such a time span. The simulation of the phenomena having a strict reference to the physical layer of the electric and TLC infrastructures, was demanded to domain specific simulators, e-Agora and NS2 respectively.

More in detail, the simulated infrastructures were modeled as follows:

Simulation tests have been devoted to analyse the spreading of service disruptions derived by different perturbing events; each simulation was executed varying the time of the first perturbation, varying the component initially affected by a negative event or the severity of the perturbations. After introducing the initial perturbation, the status of each component was traced together with the interactions among the infrastructure components and then the results were plotted using georeferenced data.

Some of these results are shown in Figure 4.11 where: the plots on the top visualise the time series of the Operative Levels of some entities; the circles on the map represents the (fake) location of the different entities and the colors of the circles represents the actual operative level.

Table 4.1: Infrastructure composition

Infrastructure	*Number of components*	*Components types*
Electric power grid	40	Power plants; Control center; Primary and secondary cabins; etc
TLC infrastructure	120	Backbone PoPs; Media gateways; Urban centrals; GSM and UMTS BTSs;etc
Air transport	2	Medium and large commercial airports
Sea transport	2	One commercial sea-port and one touristic seaport
Railway	30	Central and local rail stations; railways; Electric cabins
Highways	25	Tollgates; highway lines; highway junctions
Urban areas	6	One major urban center; 2 medium urban centers; 3 minor urban centers

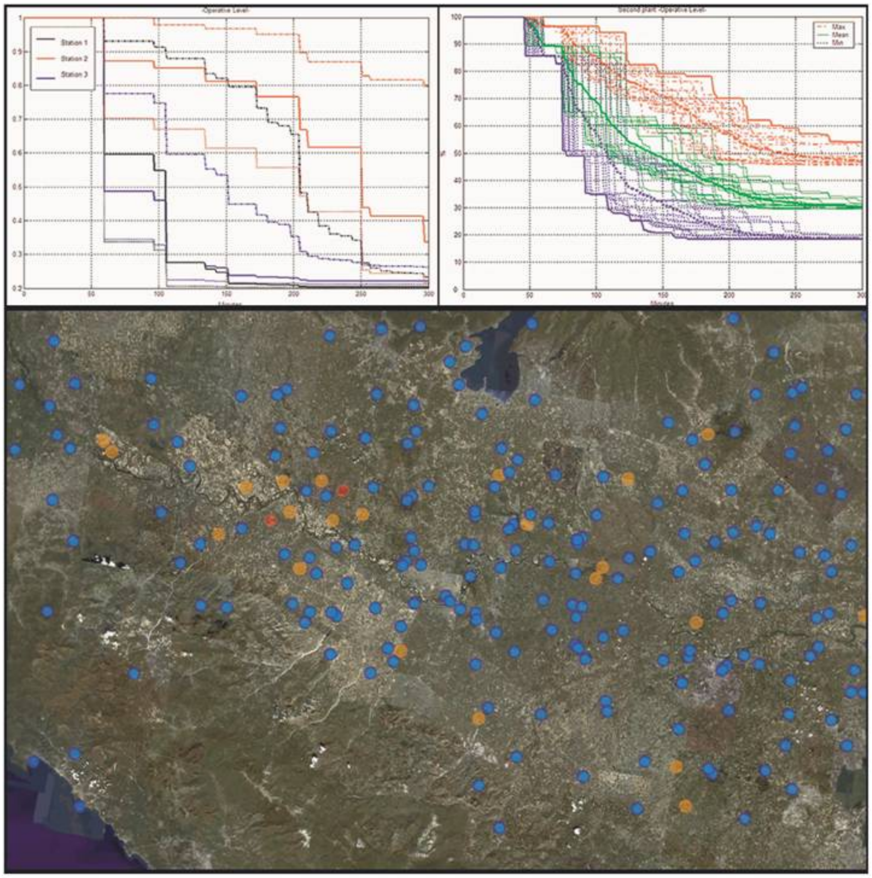


Figure 4.11: Georefenced projection of the testbed scenario (fake picture)

Stefano De Porcellinis

Chapter 5

Mixed Holistic-Reductionistic approaches

5.1 Reasons for a further improvement

Infrastructure systems and their interaction mechanisms can be interpreted followingt a multitude of different approaches, depending on different perspectives and levels of abstraction. The transition between higher abstraction levels down to deeper ones, implies a multitude of different concepts about who and what has to be considered as an elementary block (e.g., an atomic entity) in the current representation. Moreover, the transition between the holistic vision of the infrastructures and a reductionist one does not occur only along the dimension of 'size', but also spans different perspectives about the meanings of interdependence and interaction that exist between these elements.

From a holistic point of view, each infrastructure can be seen as a reality with its own identity, recognisable boundaries and functional properties, which interacts with other similar entities according to an identifiable (and reduced) set of relationships. Following such a perspective, it is easy to identify the role that each infrastructure holds in the national and international context, the economical, social or political role it plays and how it depends on other infrastructures (or how other infrastructures depend on it).

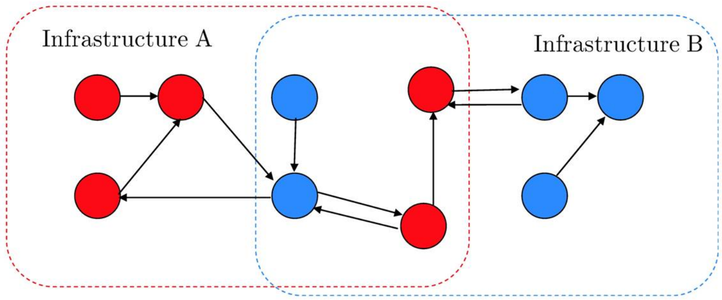


Figure 5.1: Infrastructure domains may overlap when modeling elements with a low abstraction level.

Roughly speaking, the cornerstone concept that comes from the holistic approach is the idea that each infrastructure may be considered as a unicum and modelled in such a way. Indeed, in many cases, services are provided by the infrastructure in a way that, from a user point of view, the role of each component is irrelevant. For example, mobile phone services are provided by the cellular phone infrastructure in a completely transparent way for the user. The infrastructure is able to hide from the user any local malfuntioning, using redundancy or reconfiguration capabilities in an automatic way. The specific Base Transreceiver Station (BTS) used in every moment is not crucial for the like of service itself, because it could automatically replaced in the case of a failure.
It is obvious that, under a similar perspective, the relationships that are outlined between different elements are high-level concepts that are observable from statistical data, market rules, sociological trends and strategic policies; all of the relationships and interactions that imply physical entities or tangible quantities are masked by high-level representations.

It is worth to notice that most of the global approaches that have been previously described are carried out using, at least in an implicit way, an holistic

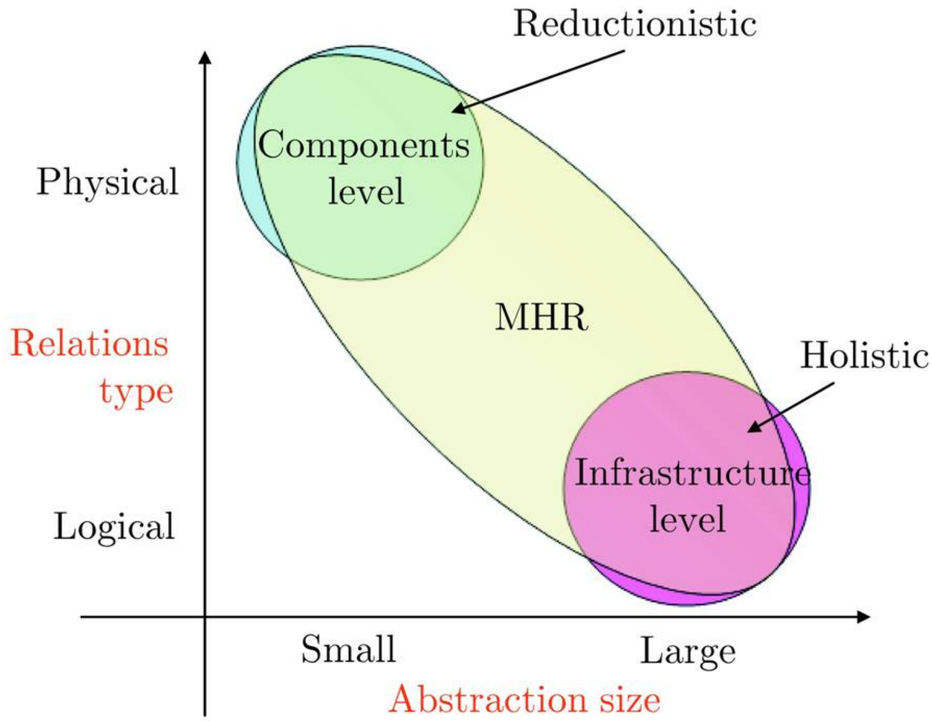


Figure 5.2: The two dimensions of interdependent infrastructures modelling

Stefano De Porcellinis

vision. Referring to Figure 5.2, this kind of approach mainly shows logical relationships among the elements and, with this perspective, the boundaries between infrastructures result crisp and well defined. At the opposite, sys-

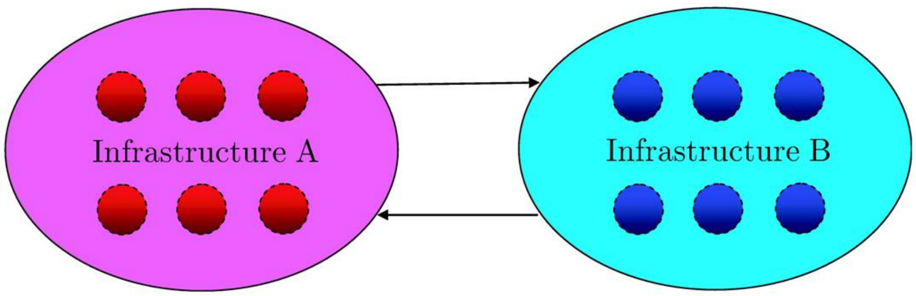


Figure 5.3: The standard way to represent interdependencies among systems. Interdependencies are modeled between layers of the same "size".

tem analysis emphasises that, in order to fully understand the dynamics and events in a complex scenario with an high level of detail, it is mandatory to capture the behaviour of each elementary component. Indeed, each component is caractezied by peculiar dynamics, requires a precise set of resources and can be affected by a finite set of failures. Then, reducing the abstraction level, it is possible to describe all of the functional elements (i.e. the technological components and the human actors) that build up an infrastructural context (see Figure 5.2). When adopting such a kind of reductionistic approaches, then, it is suitable to assign, also, a physical meaning to interaction mechanisms (see Figure 5.2), precisely describing quantities, resources and signals exchanged by the different elements. As a consequence, this perspective may lead to lose and exact definition of the boundaries among different infrastructures.

In a nut-shell, we can affirm that global approaches exploit the holistic perspective in order to infer high-level properties and behaviours of each infrastructure, while system analysis and complex networks tend to infere global behaviours from the reductionistic representation of the elements which

Stefano De Porcellinis

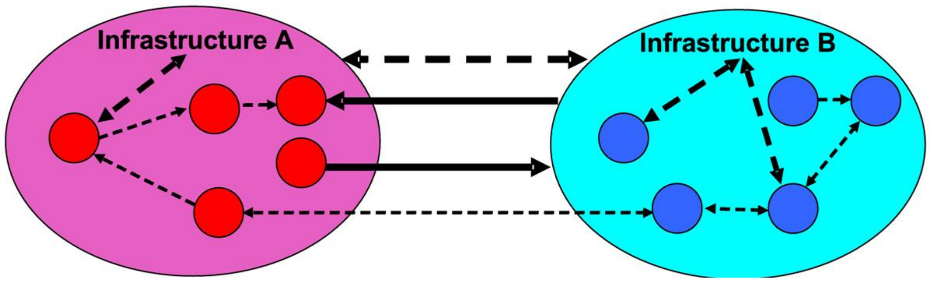


Figure 5.4: Mixed Holistic-Reductionistic approach. The interdependencies can be modeled as element-to-element, element-to-system o system-to-system.

constitute the overall system. It is evident that each one of these approaches has its scopes and shows its limits, but it is also clear that, within those scopes, it could provide useful elements to better understand the complex scenario that is set up.

5.2 Mixed Holistic-Reductionistic approach

Recent progresses in biology emphasised that complete knowledge of the elementary component (e.g. the sequencing of the genome) does not provide the full knowledge on the behaviour of the overall organism. Citing Denis Noble "reductionist information is still an important component, but only a component" [D. Noble, 2006]. In other terms, to fully understand a complex system we need to merge into a single framework reductionistic elements with holistic perspectives.

This idea is at the base of the methodology we explored in [S. De Porcellinis, S. Panzieri, R. Setola, 2009], the *Mixed Holistic-Reductionistic* approach (MHR in the following). In such a transversal approach interdependencies among components can be modeled through reductionistic techniques, while logical/functional dependencies at infrastructure level can be represented using an holistic paradigm.

Stefano De Porcellinis

As shown in Figure 5.5, this approach represents physical relations between components of single infrastructures, even if it is possible to define some cross-infrastructure dependencies among elements with low-level of abstraction (e.g. components) or, in terms of relations among infrastructures assumed as an unicum. According to such an hybrid approach, several representations of the same infrastructure, with different level of abstraction, are concurrently used in order to define the interactions among infrastructures and their elements; hence, an infrastructure is at the same time a monolithic entity and a 'set' of components. In the same way, interactions are among infrastructures at higher level or among components in a low-level perspective.

The stack-like schema, represented in Figure 5.5, highlights that both holistic and reductionistic perspectives implicitly provide *horizontal* relations among elements, while a *vertical* dimension represents hierarchical decomposition/aggregation used to express the inner relationships existing among one infrastructure and its components.

MHR pattern provides also *diagonal* links, in order to explicitly model functional relationships among heterogeneous components and infrastructures, i.e. among elements with different level of granularity and belonging to different domains (the solid lines in Figure 5.5).

Notice that, as a matter of fact, any diagonal relation can be expressed in terms of a set of horizontal and vertical dependencies. However, this approach would require to specify every single link existing among the components of one infrastructure and all the other involved elements; in this way, the complexity could explode, due to the large number of interconnections that should be considered. Moreover, many of the possibly required links are generally hidden or not well-understood from the point of view of the single component.

Therefore, representing those dependencies with a link between the components and the infrastructure as a monolithic entity helps to simplify the

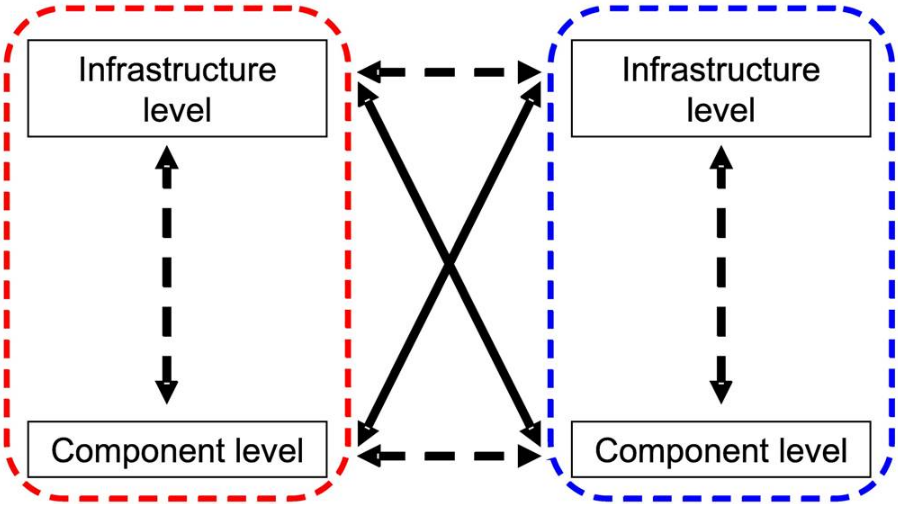


Figure 5.5: Interdependencies are modeled between different abstraction "layers".

models; from this point of view only general information about the overall status of infrastructures are required, while there is no need to know how every single component is involved in the process.

5.3 Service modelling

Although the MHR approach leads to a relevant simplification in the resulting models, it has only the ability to represent interactions among entire infrastructures and components.

However, these two layers appear not sufficiently rich to capture the complexity of critical infrastructures and their interdependencies. To overcome this limit we explored the efficacy to add in the logical schema an additional layer. This need come from the fact that interactions among elementary components and the overall structure are generally mediated by aggregates demanded to specific functions (e.g. proteins, RNA or even organs in the biological vision). We labeled these intermediate entities as *services*, because

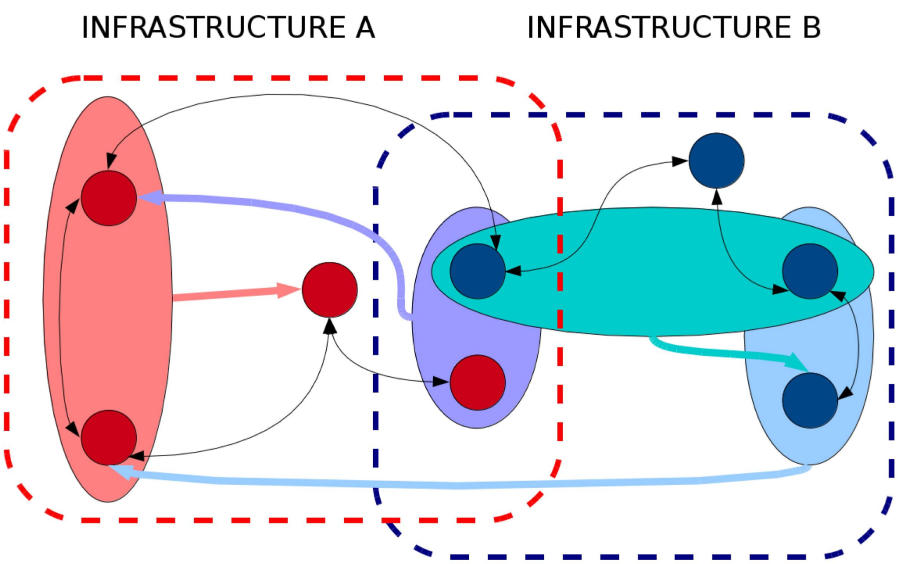


Figure 5.6: MHR model with service: services (ellipses) emerge by the cooperation of components (circles), eventually belonging to different infrastructures. Using such a perspective complex dependencies can be represented also through functional dependencies among components and services.

their relevant characteristic is the function they perform.

For example, let's consider a computer network, composed (for sake of simplicity) by interconnected servers and end-user terminals; it results evident that the existence of point-to-point communication via VoIP depends, not only on the existence of physical communication link, but even on the VoIP quality of service/status. An exact model of the dependencies for such a service could require a non-trivial effort; moreover when many services coexist in the system, such a procedure should be iterated several times.

The scheme in Figure 5.6 explains the structure of the proposed perspective. From a biological point of view, a service is not only the trivial aggragation of its components; it is an emerging entity whose bounds are no longer so easily modelled. Indeed, services are logical/functional entities, where a single component may contribute to several of them (i.e. a router in a computer network is demanded to forward information required for many coexisting services). Moreover services are not necessarily static entities, they may be activated on-demand or, even, arise in some specific situations (i.e. emergency power supply for a router in a telecommunication network).

Finally, a service can be transversal to several systems and not necessarily limited to the single context; indeed, a service existing within one infrastructure can provide its outputs also to external entities, or (less frequently) emerge by the cooperation of entities belonging to different infrastructures.

5.3.1 Overall Architecture

Figure 5.7 illustrate how the *services* are introduced into a MHR schema. As shown, the global architecture is composed of three layers:

- Macro-Component layer
- Service layer
- Infrastructure layer

With a pure reductionistic perspective, in the Macro-Component layer, each infrastructure is decomposed into its elementary components which behaviour depends, further than on the internal model, from the interactions with the other macro-components (black arrows in Figure 5.7). Moreover, their capability to correctly operate depends also by the availability and quality of some *services* (empty arrows in Figure 5.7).

At the same time, the intermediate layer represents how each infrastructure emanates its social and economic functions, providing its *services*. Obviously, the capability of each infrastructure to provide these services depends, further than on the internal dynamics of the service itself, also on the availability and quality of other services on which it depends. Moreover, this capability may be largely influenced by the operative condition of the whole system and on the *policies* or *management* strategies adopted in the specific context.

Finally, in the top layer, infrastructures are modelled with an holistic approach, as unique entities. In this layer, then, the behaviour of the "element" infrastructure depends, further than to the holistic model of the infrastructure, also on the interaction with other infrastructures (horizontal top level line in Figure 5.7). Moreover, it can depend, also, on the operational capability of every macro-component and services it could contain. Inside the element "infrastructure", these data are suitable aggregated in order to be converted, from a reductionist and service oriented data, into holistic quantities.

Note that the linkages between services and macro-component nodes are only downwards; in other terms, for a given service, the dependency on physical level nodes has not to be modeled directly. This is due to the consideration that such dependencies are mostly hidden, complex and rather not well-understood; moreover, the policies/decisions/actions performed in order to grant an acceptable quality of services are usually demanded to entities with a wider perspective. Hence, it resulted more rational that a service

Stefano De Porcellinis

entity should only rely on data provided by a manager entity, whose global awarness is able to filter the huge amount of data retrieved from the down-layer elements.

As previously exposed, the top level of each system is represented by a single node which is demanded, basing on the current availabilities of the status of its own services and macro-components (feedback arrows in Figure 5.7), to the evaluation of the actual state of the system, taking into account also the disrupting/disabling phenomena and the operative level of the other systems.

"System nodes" then, have to handle the services, to influence their operative condition (on the base of the overall system' status) and evaluate the feedback received from macro-components and other services; moreover, every system node may provide the management policies for the services through the definition and execution of adequate control actions (i.e. flow redirections, service suspension/reactivation/recovery, generation of event-driven/on-demand/emergency services...), in order to react to adverse events which may cause denial of services and further cascading propagation of faults.

In the last section we illustrate how this approach can be implemented in the CISIA framework [S. De Porcellinis, S. Panzieri, R. Setola, G. Ulivi., 2008].

5.4 MHR framework within CISIA

As exposed in the previous chapter, CISIA is a powerful tool aimed to represent and simulate interconnected infrastructures and their interdependencies with a reductionistic, yet high-level, description of the composing elements.

Therefore, in order to implement the MHR model, we introduced two additional classes of objects, *infrastructure* and *service*, also modifying the basic class used for the the macro-components.

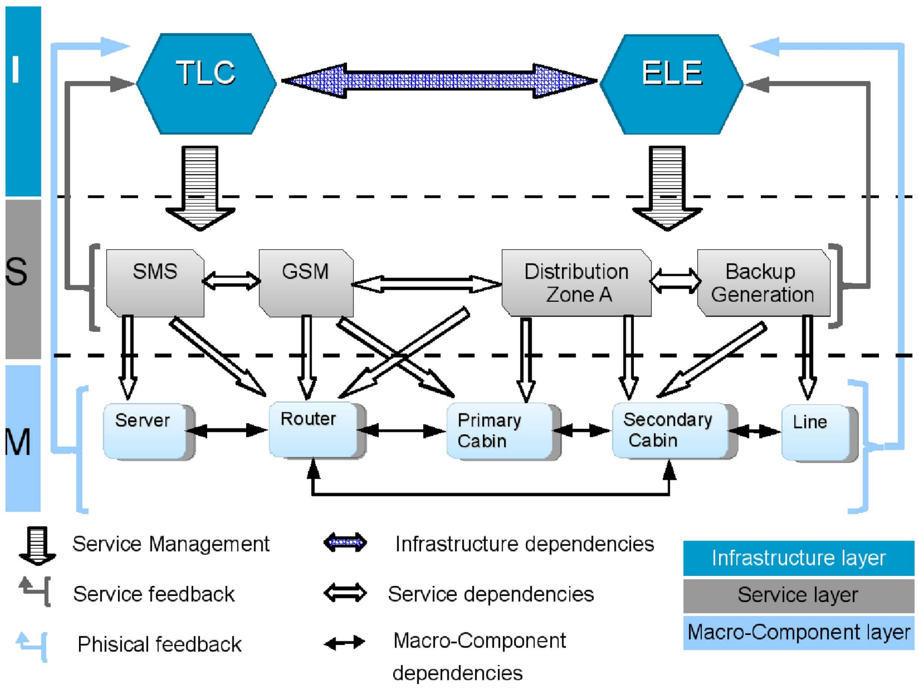


Figure 5.7: Overall MHR architecture

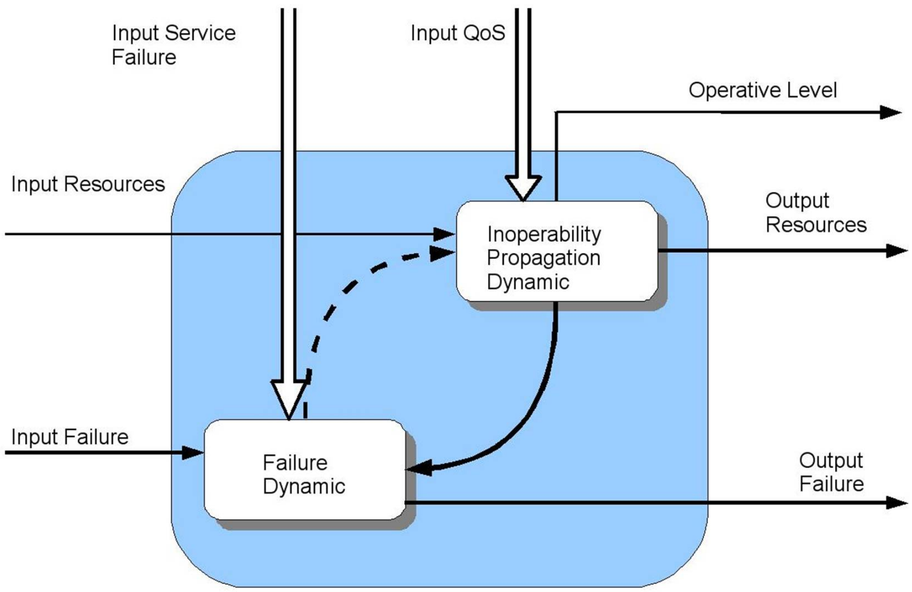


Figure 5.8: Macro-Component entity in CISIA with MHR

Indeed, as illustrated before, within the MHR framework a macro-components model (Figure 5.8) recalls the structure of basic entities in CISIA; in fact, an element in the physical layer has its own *Inoperability Propagation Dynamic* and *Failure Dynamic*. But the model has been enriched considering also the dependencies on the state of some *services*, in terms of quality of such services and severity of the faults that may affect them.

Analogously, *services* can be described through a block scheme (see Figure 5.9) which considers the specific *Inoperability Propagation Dynamic* on the base of the intrinsic model of the service itself while considering the *QoS* of the other services on which it depends. These dynamics are also affected by the *service*'s *Failure Dynamic*, which depends on internal and propagated failures. Notice that, the introduction of specific *Failure Dynamic* at service level allows to model software failures (e.g. software virus) that, instead, might be very complex to model at the components level.

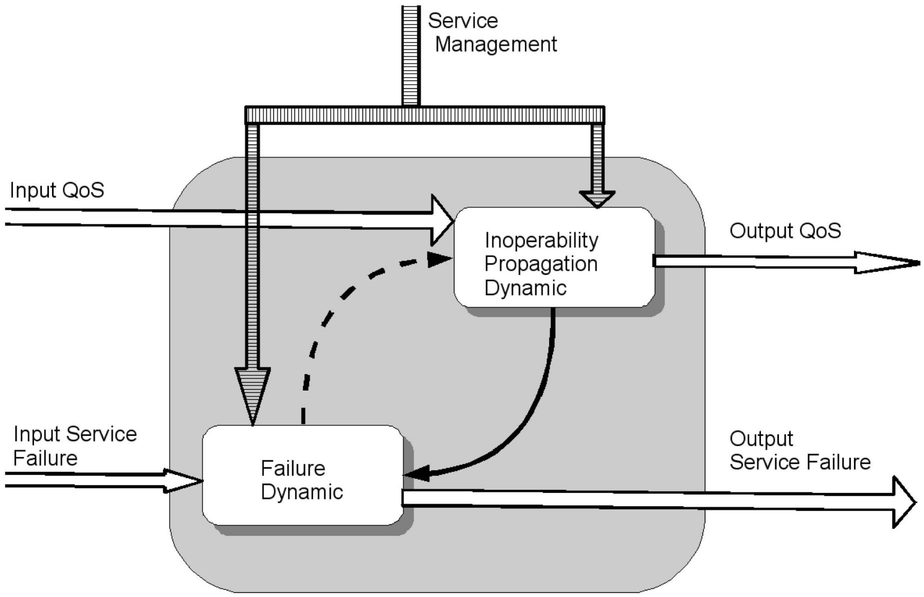


Figure 5.9: Service entity in CISIA with MHR

Infrastructure nodes (see Figure 5.10) represent the holistic view of the infrastructure, and thus they have their own *Inoperability Propagation Dynamic* and *Failure Dynamic*, and they interact with other infrastructure nodes exchanging their Operative Level. In this case the failure block allows to model specific system wide events (e.g. strike) that could result very difficult to model using high detail levels.

On the other hand, every system receives feedbacks about the state of its own macro-components and services and about the severity of faults affecting them. Such high detail information are merged within the *Aggregator* block, in order to be translated into more abstracted and aggregated information, used to drive the overall system behaviour. At the same time, the *Service Manager* has the duty to influence the operative condition of services, setting up the corresponding constraints and policies.

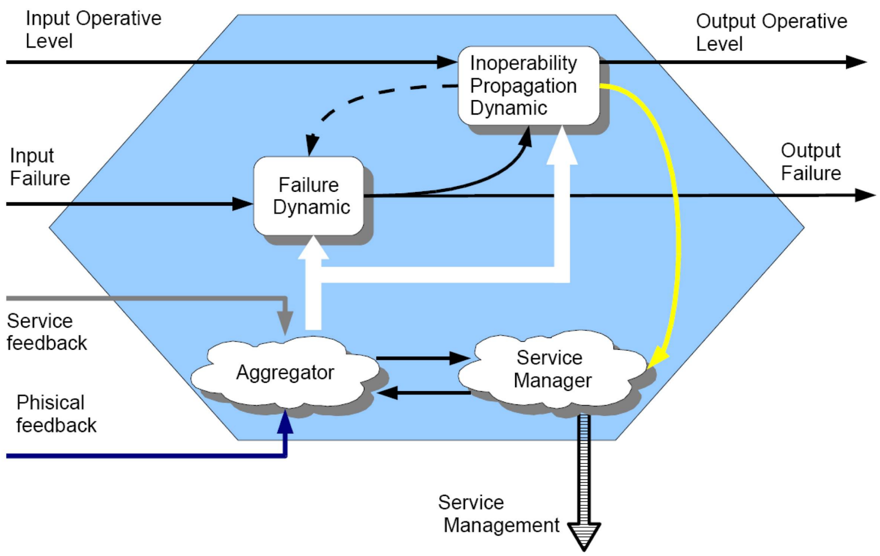


Figure 5.10: Infrastructure entity in CISIA with MHR

Stefano De Porcellinis

Conclusions

There are two aspects which, if properly analysed, allow us to gain relevant insights on complex systems:

- The analysis of the topologies of the underliyng *graphs*, mainly aimed to unveil their structural properties;
- The study of the "behaviours" that emerge from the functional interactions among the different components..

Topological analysis of graphs underlying large and complex systems takes the move from the pioneering works of Strogartz and Barabasi [D.J. Watts, S.H. Strogartz, 1998, A.L. Barabási, 2001], who emphasised the presence of the *selective pressure*, able to determine common growth mechanisms in a number of different complex systems (from those representing technological systems to those related to biological and social networks).

In the present Thesis, I have illustrated several modeling techniques that have been specifically developed with the aimed to handle the complexity of a scenario composed by several and heterogeneous elements that interact in an unsupervised manner.

The first models we explored were the functional topology-based models, which revealed particularly suitable to model complex system when there are available simplified but realistic representations of the physical behaviours of elements which form the system. Such models, therefore, show some limits when the analysis has to take into account multiple interactions among those elements and among different systems.

In order to develop methodologies which might result adequate when it was required to understand the effects of high-order interactions among different systems, we focused our attention on IIM-based approaches. Such approaches, are based on an holistic abstraction formulation and, complemented with the use of fuzzy numbers, resulted very useful when analysing etherogeneous complex systems in the presence of scarce or ill-formed data.

At the same time, we persecuted the development of simulative methodologies and tools aimed to the implementation of reductionistic models. Our reductionistic approaches, indeed, permitted to overcome some of the limits imposed by the simplified IIM-based models, enabling the description of highly detailed dynamics and interaction mechanisms. Also in this case, the use of fuzzy numbers, enabled to cope with the data retrieved from experts interviews which often present vague descriptions or confounding information. Also the development of federated simulation environments have been explored.

In the last year of rearch, taking the move from the previous experiences, an innovative hybrid approach has been formulated. Staring from the consideration that each one of the previously explored approaches presented, in the analysis of etherogeneous complex systems, specific benefits and weak points, we developed the MHR Method, with the aim to merge those approaches in a unified framework.
Up to now, the MHR is revealing to be a very powerful tool, especially when we have to deal with complex systems which are composed by many dfferent elements and when such elements, and the systems themselves, base their existence on mechanisms which result from their cooperation, at different scales and organizative levels.
As a last note, it is worth to notice that a similar 'reconstructive' approach has, nowadays, an onward success in many and different academic disciplines.

Indeed, the progressive enhancing of technological means enabled the scientists to obtain a very deep knowledge about atomic or sub-atomic phenomena and the sequencing of the complete human genoma is also a reality. At the same time, with the same extremely powerful tools, we are not yet able to understand many of mechanisms which drive the existence of complex systems.
Often we are able to observe with the microscope the pigments on the canvas, but we are not able to see the whole painting... The need for recomposing approaches is paramaunt.

Appendix A DC Power-Flow Model

The DC power flow equations [A.J. Wood, B.F. Wollenberg, 2004] provide a linear relationship between the active power flowing through the lines and the power input into the nodes. They can be formulated as it follows:

$$F_{km} = \frac{\theta_k - \theta_m}{x_{km}} \tag{5.1}$$

where x_{km} is the series reactance of the line connecting nodes k and m, F_{km} is the active power flow on this line and θ_k, θ_m are the voltage phase of the k'th and m'th node. Summing on all branches connected the node k the power flow of that node P_k is

$$P_k = \sum_m F_{km} = \theta_k \sum_m x_{km}^{-1} - \sum_m \frac{\theta_m}{x_{km}} \tag{5.2}$$

this can be written in a matrix form

$$\mathbf{P} = \mathbf{B}\theta \tag{5.3}$$

where θ is the vector composed by voltage phase at the N nodes of an electric grid,$B_{km} = -1/x_{km}$ and $B_{kk} = \sum_l 1/x_{kl}$; $\mathbf{B}$ is a $N \times N$ matrix. The rank of $\boldsymbol{B}$ is $N-1$, since the network must comply the conservation condition

$\sum_{i=1}^{N} P_i = 0$. To solve the system, an equation is removed and the associated link is chosen to introduce a reference node, whose phase angle is arbitrarily set to $\theta = 0$. For a given input vector $\mathbf{P^{(0)}}$, the linear system in eq. (5.3) can be solved and a solution is found in terms of θ_i and F_{ij}. Two constraints must be imposed to ensure the physical correctness of the solution. This comes from the fact that the DC power flow method results from the elimination of the imaginary part of the current equations, under the hypothesis that power phase angles are small. For such a reason, it should result, $\forall (k, m)$, that

1. $\theta_k < 30$ degrees

2. $\mid F_{km} \mid < F_{km}^{max}$ (where F_{km}^{max} is a specified limit on power flux on the link between nodes k and m).

If constraint (1) is not fulfilled, the inductive part of the electrical flux cannot be disregarded and eq.(5.3) does not hold. Constraint (2) is a technological threshold, relating the specific line's impedance. Flux too large produce unendurable heat normally prevented by *ad hoc* elements which disconnect the line.

Then, selected a $\mathbf{P^0}$, i.e. a typical snapshot of the vector (injected power–extracted power) experienced daily in the electric grid, one can use (5.3) to evaluate:

- (1) the power flux F_{ij} along the lines resulting from the given input vector $\mathbf{P^{(0)}}$;

- (2) the phase angles θ_i.

Notice that source nodes are characterized by negative P_i values, junction by vanishing values, loads by positive values.

The solution of the DC power flow system will constitute the "normal" response of the network to the input conditions $\mathbf{P^{(0)}}$.

Appendix B Fuzzy Numbers

FNs can be seen as the most natural way to introduce and model data uncertainty in a technical talk. Consider the simple statement from an expert "the energy supply will last for about two days". According to a brief interview with an expert, we can represent the value "about two days" with one of the diagrams in Figure 5.11. Here the so-called triangular FNs are assumed. In particular, the larger plot represents "I am maximally confident that it can last two days and I am sure it cannot last less than one day or more than three", while the thinner one shows less uncertainty. FNs can actually have any shape, the most common being triangular, trapezoidal and Gaussian. The difference in their representation implies different computational cost for their handling, simpler shapes can be represented with less parameters, while higher order polynomial shapes require to be sampled over a consistent range of values.

Without lost of generality, here triangular FNs are considered. They can be memorised using the ordered triples representing the abscissa of the three vertices. The extension of the arithmetic operations is immediate for sum and subtraction. Indeed, these are linear operations and the resulting FN is also triangular. For example, representing two triangular FNs A and B with the triples $[a1, a2, a3]$ and $[b1, b2, b3]$, their sum is simply obtained as $[a1 + b1, a2 + b2, a3 + b3]$.

On the contrary, multiplication of two triangular FN produces an FN whose sides are parabola segments. It is easy to see that multiplying two

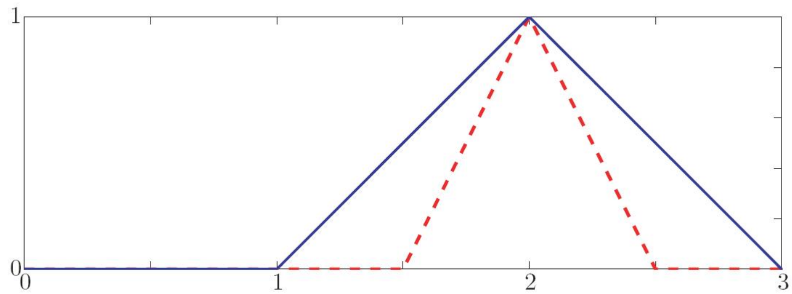


Figure 5.11: Triangular Fuzzy Numbers (FNs) representation.

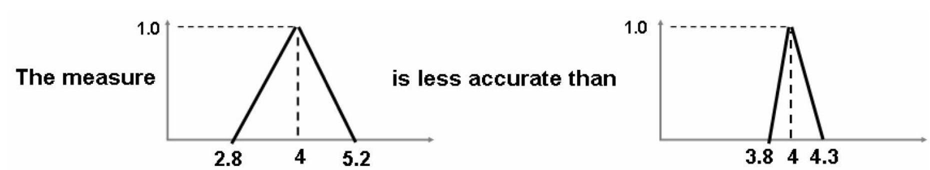


Figure 5.12: The accuracy of FN is related to the dimension of interval with a degree of membership $\mu(x) > 0$ (i.e. the support of the number).

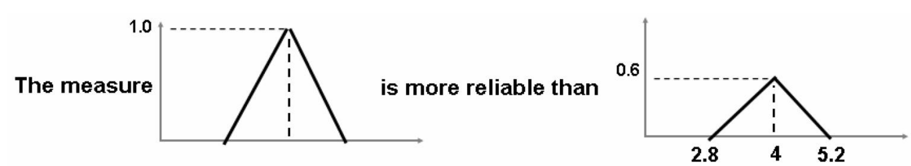


Figure 5.13: The reliability of the FN is proportional to the highest degree of membership.

parabolic FN, the result is described in terms of fourth order polynomials and so on. So, exact computations can easily become unmanageable, in particular in iterative procedures like those required in simulations. Two strategies are typically used to solve this problem. The first one consists in discretising the FN over the range of all the possible values. This means a huge consumption of both computational and memory resources and, in any case, introduces some errors due to the discretisation. The second solution is the approximation of the parabolic FN with a triangular one, avoiding the increase of complexity. In this case the product of FNs A and B is simply given by $[a1b1, a2b2, a3b3]$. The case of division can be managed in the same way, once it is verified that the three values representing the divisor have all the same sign. A division by zero would imply a poor system modelling. A different problem is posed moving to comparison. Typically, in fuzzy logic, the result of a comparison is a fuzzy quantity so that we can say that "A is a little greater then B" or is "much greater than B". Even if there are some experimental tentatives to use this fuzzy information in programming, we have preferred to defuzzify the result before using it. To this aim, in order to compute $B > A$, the centre of gravity of $B - A$ is compared with zero. For formal definitions and more details see [C. Chiu, W. Wang, 2002]; [R.E. Giachetti, R.E. Young, 1997] and [T. Ross, 2004]. In the presented work, fuzzy numbers are used mainly as an extension of interval arithmetic. Actually, they represent our believe in a given assertion and are more flexible to use than the "a priori" probability. A complete analysis of the relation between probability and fuzzy measures can be found in [D. Dubois, H. Prade, 1998] or in the Appendix A of [T. Ross, 2004].

Bibliography

A.J. Wood, B.F. Wollenberg. Power generation, operation and control. 2004.

A.L. Barabási. Lethality and centrality in protein networks. *Nature*, 2001.

A.M.E. Luiijf, H.H. Burger, H.A.M. Klaver. A Critical (information) Infrastructure Protection in The Netherlands. In *Proc. Critical Infrastructure Protection (CIP) Workshop*, Frankfurt, Germany, Sept. 29–30 2003.

C. Chiu, W. Wang. A simple computation of max and min operations for fuzzy numbers. *Fuzzy Sets and Systems*, 126:273–276, 2002.

C.H. Chiu, W.J. Wang. A Simple Computation Of Max And Min Operations For Fuzzy Numbers. *Fuzzy Sets end Systems*, 126:273–276, 2002.

D. Dubois, H. Prade. *Possibility Theory: an Approach to Computerized Processing of Uncertainty*. Plenum Publishing Corporation, New York, 1998.

D. Noble. *The Music of Life*. 2006.

D. Reinermann, J. Weber. Analysis of Critical Infrastructures: The ACIS Methodology. In *Proc. Critical Infrastructure Protection (CIP) Workshop*, Frankfurt, Germany, Sept. 29–30 2003.

D. Watts, S. Strogartz. Collective dynamics of 'small-world' networks. *Nature*, 393:440–424, July 1999.

D.E. Newman, B. Nkei, B.A. Carreras, I. Dobson, V.E. Lynch, P. Gradney. Risk Assesment in Complex Interacting Infrastructure Systems. In *Proc. of 38th Hawaii Int. Conf. on System Science*, Big Island, Hawaii, Jan.3–6 2005.

D.E. Newmanand, B. Nkei, B.A. Carreras, I. Dobson, V.E. Lynch, P. Gradney. Risk assessment in complex interacting infrastructure systems. 2005.

D.J. Watts, S.H. Strogartz. Collective dynamics in small–world networks. *Nature*, 1998.

E. Casalicchio, E. Galli, S. Tucci. Agent-based Modeling of Interdependencies in Critical Infrastructures through UML. *Proc. of Spring Simulation Multiconference 2007/Agent Discrete Simulation 2007*, 2007.

E. Casalicchio, P. Donzelli, R. Setola, S. Tucci. Modelling and Simulation of Interdependent Critical Infrastructure: The Road Ahead. In *Modelling to Computer Systems and Networks*. Imperial College Press, London, UK, 2006 (to be pubblished).

E.U. Commission. *Green Paper on a European Programme for Critical Infrastructure Protection COM(2005)576*. Brussels, 2005.

F. Tiriticco, S. Bologna, V. Rosato. Topological properties of high-voltage electrical transmission networks. *Electr. Power Syst. Res.*, 2006.

Government of Canada, Office of Critical Infrastructure Protection and Emergency Preparedness (OCIPEP). *Threats to Canada's Critical Infrastructure*. Mar. 2003. URL `www.ocipep.gc.ca/opsprods/other/TA03-001_e.asp`. TA03-001.

Italian Government Working Group on Critical Information Infrastructure Protection (PIC). *La Protezione delle Infrastrutture Critiche Informatizzate - La Realtá Italiana*. Mar. 2004. (in Italian).

J. Moteff, C. Copeland, J. Fischer. Critical Infrastructures: What Makes an Infrastructure Critical? In *Report for Congress RL31556*. The Library of Congress, Aug. 2002. URL `www.fas.org/irp/crs/RL31556.pdf`.

J. Moteff, G. Stevens. Critical Infrastructure Information: Disclosure and Homeland Security. In *Report for Congress RL31547*. The Library of Congress, Jan. 2003. URL `www.fas.org/sgp/crs/RL31547.pdf`.

K. Hopkinson, K. Birman, R. Giovanini, D. Coury, X. Wang, J. Thorp. EPOCHS: Integrated Commercial Off-the-Shelf Software for Agent-Based Electric Power and Communication. In *Proc. Winter Simulation Conference*, pages 1158–1166, New Orleans, Luisiana, Dec. 7–10 2003.

K.G. Crowther, Y.Y. Haimes. Applications of the inoperability input-output model (IIM) for systemic risk assessment and management of interdependent infrastructures. *Systems Engineering*, 8(4):323–341, 2005.

M. Amin. Modelling and Control of Complex Interactive Networks. *IEEE Control System Magazine*, pages 22–27, 2002.

M. Dunn, I. Wigert. International ciip handbook. ETH, The Swiss Federal Institute of Technology, Zurich, 2004. URL `www.isn.ethz.ch/crn/publications/publications_crn.cfm?pubid=224`.

M. Permann, M. Manic. Cims: A framework for infrastructure interdependency modeling and analysis. *Proceedings of the Winter Simulation Conference 2006 (WSC 06)*, pages 478–485, 2006.

M.E.J. Newman. Models of the Small World: A Review. *Journal of Statistic Physics*, 101, 2000. URL `http://www.citebase.org/cgi-bin/citations?id=oai:arXiv.org:cond-mat/0001118`.

P. Crucitti, V. Latora, M. Marchiori. A topological analysis of the italian electric power grid. *Physica A*, 2004.

P. Echenique, J. Gomez-Gardenes, Y. Moreno. Improved routing strategies for internet traffic delivery. *Phys. Rev. E*, 2004.

P. Jiang, Y.Y. Haimes. Risk management for leontief–based interdependent systems. *Risk. Analysis*, 2004.

R. Albert, A.–L. Barabási. Statistical mechanics of complex networks. *Rev. Mod. Phys.*, 2002.

R. Albert, A. Barabási. Statistical Mechanics of Complex Networks. *Reviews of Modern Physics*, 74:48–97, 2002.

R. Albert, A.Baràbasi. Statistical mechanics of complex network. *Reviews of Modern Physics*, 74(47), 2001. URL `http://www.citebase.org/cgi-bin/citations?id=oai:arXiv.org:cond-mat/0106096`.

R. Albert, H. Jeong, A. Barabási. Error and Attack Tolerance of Complex Networks. *Nature*, 406:378–382, 2000.

R. Albert, I. Albert, G.L. Nakarano. Structural vulnerability of the north american power grid. *Phys.Rev.E*, 2004.

R. Benoit. A Method For The Study Of Cascading Effects Within Lifeline Networks. *Int. Journal of Critical Infrastructure*, 1:86–99, 2004.

R. Macdonald, S. Bologna. Advanced Modelling and Simulation Methods and Tools for Critical infrastructure Protection. Technical report, Jun. 2001. ACIP project report.

R. Pastor–Satorras, A. Vasquez, A. Vespignani. Dynamical and correlation properties of the internet. pages 28–29, 2001.

R. Setola. Analysis of interdependencies among Italian economic sectors via Input-output Inoperability Model. *Annual IFIP International Conference on Critical Infrastructure Protection, Malaga (ES)*, 2007.

R. Setola, G. Ulivi. Modelling Interdependent Critical Infrastructure. In N. E. Mastorakis, editor, *Recent Advances in Intelligent Systems and Signal Processing*, Electrical and Computer Eng. Series, pages 366 – 372. WSEAS press, 2003.

R.E. Giachetti, R.E. Young. A Parametric Representation Of Fuzzy Numbers And Their Arithmetic Operators. *Fuzzy Sets end Systems*, 91:185–202, 1997.

S. Asavathiratham, B. Leiseutre, G. Verghese. The Influence Model. *IEEE Control System Magazine*, pages 52–64, 2001.

S. Boccaletti et al. Complex networks: Structure and dynamics. *Phys. Reports*, 2006.

S. Bologna, R. Setola. The Need to Improve Local Self-Awareness in CIP/CIIP. In *Proc. First IEEE International Workshop on Critical Infrastructure Protection (IWCIP 2005)*, pages 84–89, Darmstadt, Germany, Nov. 3–4 2005.

S. De Porcellinis, S. Panzieri, R. Setola. Model critical infrastructure via a mixed holistic-reductionistic approach. *Int. J. Critical Infrastructures (IJCIS)*, 2009.

S. De Porcellinis, S. Panzieri, R. Setola, G. Ulivi. Simulation of heterogeneous and interdependent critical infrastructures. *Int. J. Critical Infrastructures (IJCIS)*, 4:110–128, 2008.

S. De Porcellinis, S. Panzieri, R. Setola, G. Ulivi. Simulation of Heterogeneous and Interdependent Critical Infrastructures. *Int. J. Critical Infrastructure (IJCI)*, pages 110–1285, 2008.

S. Panzieri, R. Setola. Failures propagation in critical interdependent infrastructures. *Int. Journal of Modelling, Identification and Control (IJMIC)*, 3(1):69–78, 2008. doi: 10.1504/IJMIC.2008.018186.

S. Panzieri, R. Setola, G. Ulivi. An Agent Based Simulator For Critical Interdependent Infrastructures. In *Proc. 2nd Int. Conf. on Critical Infrastructures (CRIS 2004)*, Grenoble, France, Oct. 26–2 2004.

S. Panzieri, R. Setola, G. Ulivi. An Approach to Model Complex Interdependent Infrastructures. In *Proc. 16th IFAC World-Congress 2005*, Praha, Czech Republic, July 4–8 2005.

S. Rinaldi, J. Peerenboom, T. Kelly. Identify, Understanding, and Analyzing Critical Infrastructure Interdependencies. *IEEE Control System Magazine*, pages 11–25, 2001.

S. Rosenbush. Satellite's death puts millions out of touch. *USA Today*, 21 May 1998.

T. Ross. Fuzzy Logic With Engineering Applications. *Chapter 12. J.Wiley and Sons Ltd.*, 2004.

T.E. Drabeck, D.A. McEntire. Emergent Phenomena and the Sciology of Disaster: Lessons, Trends, and Opportunities from the Research Literature. *Disaster Prevention and Management*, 12(2):97–112, 2003.

The IRRIIS European Integrated Project. www.irriis.org.

The NISAC (National Infrastructures Simulation and Analysis Centre). www.sandia.gov/mission/homeland/programs/critical/nisac.html.

T.J. Ross. *Fuzzy Logic With Engineering Applications*, chapter 12. J. Wiley and Sons Ltd., 2004.

U.N. 58th Generally Assembly. *Creation of a Global Culture of Cybersecurity and the Protection of Critical Information Infrastructures*. Number UN-58/159. Dec. 2003. URL `www.un.org/Depts/dhl/resguide/r58.htm`.

U.S. and Canada Power System Outage Task Force. *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations*. Apr. 2004. URL `https://reports.energy.gov/`.

U.S. General Accounting Office. *Critical Infrastructure Protection: Challenges for Selected Agencies and Industry Sectors*. Feb. 2003. URL `www.gao.gov`. GAO-03-233.

U.S. Government. *The National Strategy for The Physical Protection of Critical Infrastructures and Key Assets*. The White House, Washington, USA, Feb. 2003a. URL `www.whitehouse.gov/pcipb/physical.html`.

U.S. Government. *The National Strategy to Secure Cyberspace*. The White House, Washington, USA, Feb. 2003b. URL `www.whitehouse.gov/pcipb`.

U.S. Government (The Executive Office of the President and the Office of Science and Technology Policy). *The National Plan for Research and Development in Support of Critical Infrastructure Protection*. Washington, USA, Apr. 2005. URL `www.dhs.gov/dhspublic/interweb/assetlibrary/ST_2004_NCIP_RD_PlanFINALApr05.pdf`.

V. Rosato, L. Issacharoff, D. Caligiore, F. Tiriticco, S. Meloni. Is the topology of the internet network really fit to its function ? *Phys. Rev. E*, 2004.

V. Rosato, L. Issacharoff, S. Bologna. 'influence of the topology on the power flux of the italian high-voltage electrical network. *Phys. Rev. E*, 2006.

V.Rosato, L.Issacharoff, S.Bologna. Influence of the topology on the power flux of the italian high-voltage electrical network. *Europhys. Lett. submitted.*, 2004.

Y. Haimes, P. Jiang. Leontief-based Model of Risk in Complex Interconnected Infrastructures. *Journal of Infrastructure Systems*, pages 1–12, 2001.

Stefano De Porcellinis

Y.Y. Haimes, B.M. Horowitz, J.H. Lambert, J.R. Santos, C.Lian, K.G. Crowther. Inoperability input-output model (IIM) for interdependent infrastructure sectors: theory and methodology. *ASCE Journal of Infrastructure Systems*, 11(2):67–79, 2005.

Y.Y. Haimes, B.M. Horowitz, J.H. Lambert, J.R. Santos, K. Crowther, C. Lian, A. Srinivasan. Applying Inoperability Input-Output Model (IIM) to the Impact of High-Altitude Electromagnetic Pulse (HEMP) on Interdependent Infrastructure Sector. *Report to the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack, Center for Risk Management of Engineering Systems, University of Virginia, Charlottesville, VA*, 2004.

Y.Y. Haimes, B.M. Horowitz, J.H. Lambert, J.R. Santos, K.G. Crowther, C. Lian. Inoperability input-output model (IIM) for interdependent infrastructure sectors II: Case Studies. ASCE. *ASCE Journal of Infrastructure Systems*, 11(2):80–92, 2005.