# Infrastructure interdependency analysis:

## Introductory research review



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Feasibility Study on Interdependency Analysis

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## Executive summary

The Centre for the Protection of National Infrastructure (CPNI), the Technology Strategy Board (TSB) and the Engineering and Physical Sciences Research Council (EPSRC) have commissioned a feasibility study to identify the state-of-the-art in Critical Infrastructure (CI) interdependency modelling and analysis, and to develop a strategy for research and practice, aiming to bridge the gaps between existing capabilities and Government/industry requirements.

This study has been conducted by the Centre for Software Reliability (CSR) of City University London, Adelard LLP and Cranfield University, UK Defence Academy for the Centre for the Protection of National Infrastructure, (CPNI) the Engineering and Physical Sciences Research Council (EPSRC) and the Technology Strategy Board (TSB).

The main report that discusses the proposed strategy can be found in [1]. This report is complimentary to [1] and presents an introductory review of research in infrastructure interdependency modelling and analysis. In particular, it focuses on network models, interdependency analysis, infrastructure models, simulation under federation and visualization.

The review draws upon a number of sources, ranging from research publications to a review of past and current European Commission-funded research projects, as well as the applied state-of-the-art in the development and application of tools and services in the area of CI simulation and analysis.

It should be noted that this research review does not attempt to be exhaustive. Rather, it has been both broad and selective, presenting work that has been identified as contributing to areas discussed in the main report, and providing signposting towards other reviews and useful publications. More attention is given to work specifically published as interdependency work and we apologize for any bias this may introduce.

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# 1 Introduction

The resilience of Critical Infrastructures (CI) can be both facilitated and undermined by dependencies between infrastructure components, processes and procedures. The understanding of complex infrastructure interactions, their dependencies and the implications of these dependencies is therefore important for achieving resilient systems, both when designing them and dealing with a crisis. Our understanding of infrastructure interactions and dependencies can be facilitated by modeling and analysis methods, techniques and software tools.

This document presents a review of research in infrastructure interdependency modeling and analysis. The review supports a study that City University London, Adelard LLP and Cranfield University carried out for the Centre for the Protection of National Infrastructure, (CPNI) the Engineering and Physical Sciences Research Council (EPSRC) and the Technology Strategy Board (TSB); this feasibility study, reported in [1] proposes a strategy for the future, aiming to bridge the gaps between the requirements of industry and Government and current capabilities in infrastructure modeling, analysis and protection.

We aim to be sufficiently broad in order to illustrate the main avenues of current research and provide signposting to other reviews and related work. We have had to focus the review as so many threads of work could be included. We have therefore done this by basing the review on the overall architecture of infrastructure interdependency modeling used in the main report (Figure 1). This research review focuses on certain components of this architecture, namely interdependency analysis, infrastructure models and simulation and visualization. More attention is given to work specifically published as interdependency work and we apologize for any bias this may introduce.

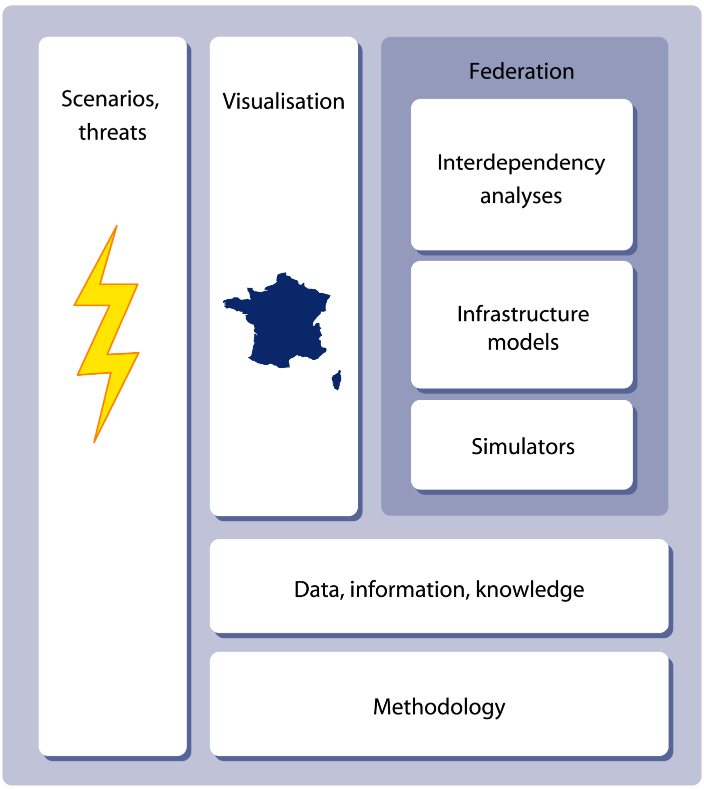



**Figure 1: Modelling components**

The review draws upon a number of sources. It incorporates, with permission, part of a review paper written within the EU project IRRIIS (Integrated Risk-Reduction of Information-based, Infrastructure Systems) [37]. Other sources of information the reader might like to look at are:

- The results of the US survey conducted by Idaho National Laboratory, US Department of Energy [40].
- Various influential publications such as [84] on infrastructure interdependencies, [85] describing modelling approaches and skills required for infrastructure interdependency analysis, including engineers, economists, social scientists, lawyers and risk analysts. and [74] which considers ten CI analysis schemes.
- Work of specific laboratories such as the National Infrastructure Simulation and Analysis Centre (NISAC) at the US Sandia National Laboratories (SNL) and Los Alamos National Laboratory (LANL) which have developed several modelling and simulation tools and techniques. Some of these are presented in [72] and [73].
- The results of relevant recent EU projects, such as IRRIIS [2] and CRUTIAL [45]

This report is structured as follows: Section 2 summarises generic–network models. Section 3 highlights work done on service-level modelling of particular networks. Topological analysis of existing networks is the subject of Section 4. Section 5 discusses simulations, both of single and multiple infrastructures. Section 6 concerns visualization. Finally, Section 7 contains a presents a categorization of models based on the general applicability of their results, our conclusions and discussion.

# 2 Models of Generic networks

CIs share several similar characteristics with other large networks (such as the World Wide Web). Networks have components/assets/resources whose states directly depend—in a causal sense—on the state of other components. In addition, several types of large networks can be seen to share many properties of graphs (whether local or large scale properties of graphs) [11][12]. For example, graph topologies with *scale-free*[1] properties have been identified as being characteristic of graphs that model the growth of the World Wide Web, social networks and neural networks.

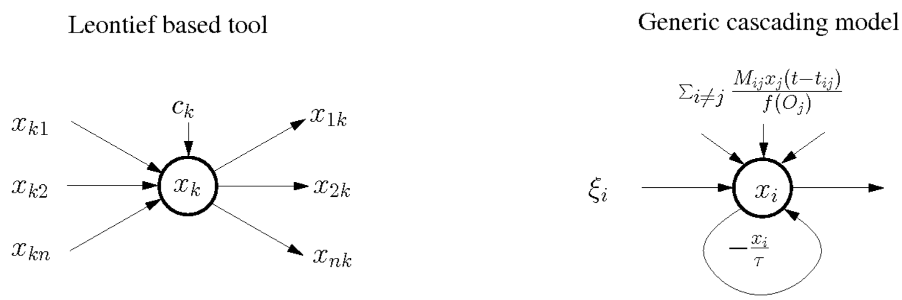
This section reports on models based on generic network-topologies. The models use graphs (a set of nodes/vertices and edges/links) to characterise infrastructures and their properties. These graphs are either an approximation of the physical configuration of the system components and their interconnectivity [13] or a description of logical dependencies between the components [14]. In what follows we summarise two developed models for causal network analysis; the *Leontief-based model* (LBM) and *Generic cascading models* (GCM). We also review a *Common-mode failure* (CMF) model and conclude with a comparison study of *stationary and dynamic cascading models*.

[1] *Scale-free* refers to a characteristic of the probabilistic law for how many nodes a given node in a network, at a given point in time, is connected to. The mathematical form of the law is unchanged by the size of the graph; consequently, the law is *scale-free*.

## 2.1 Models of Causal Networks

The study of causal relations can facilitate the better understanding of the non-intuitive implications of decisions, and their consequences on the behaviour of complex system. Logical dependencies between the system components, or potential events and their consequences, can be characterised by (*causal*) *networks*. Here, causal relations among different events or operation states are represented by oriented graphs. Graph nodes represent system components, services or events and each node is described by state variable $x$. When the state of one node can be influenced by another, the nodes are connected by a link.

To assess the impact of interdependencies among the interconnected systems LBM interprets the causal network as an interconnected critical infrastructure system. *Operability* of each node represents the state of one system or system component. The Leontief-type equation [18], originally used to characterise economic systems, has been reformulated to the form shown in Figure 2. For a concrete causal network and interdependency matrix this model allows one to analyse the impact of perturbations on system operability, to estimate the consequences of interdependencies and to compare the efficiency of different buffering strategies.




$$x_i(t+1) = \min\{1, \Sigma_{j=1}^{n} \rho_{ij} x_j(t) + \gamma_i d_i(t)\} \qquad \frac{dx_i}{dt} = -\frac{x_i}{\tau} + \theta\left(\Sigma_{i \neq j} \frac{M_{ij} x_j(t-t_{ij})}{f(O_i)} e^{-\beta t_{ij}/\tau}\right) + \xi_i(t)$$

**Figure 2: The Leontief and general cascading models**

GCM has been developed in order to study the impact of network topology and various parameters on the spreading of failures in directed networks. The model combines network nodes as active bistable elements described by the equation shown in Figure 2. The model considers the recovery capacity of system components and time-delayed interaction among the nodes. Extensive computer simulations revealed that the topology of the interaction network plays a crucial role for the transition between the spreading and non-spreading regimes and the expected damage radius [16]. In addition, the model was used to assess the efficiency of different recovery strategies [17].

Both models apply similar ideas. However, the equations characterising the network behavior have some differences. LBM moves forward in discrete time steps, while GCM is continuous. The sustainability of nodes is also represented differently; LBM uses buffers while GCM implements, directly in the equation, the recovery term characterised by parameter $\tau$. The main functional difference is that LBM can be used to analyse the in-operability dynamics as a consequence of perturbations for smaller networks while GCM is more appropriate for studying spreading behavior in larger networks.

## 2.2 Common-mode Failure Model

Under certain operational conditions, the components of a complex network may be more likely to fail coincidentally than otherwise. For instance, the large North American power outage of November 2005 [19] was caused, in part, by the correlated failure of both primary and secondary software channels in General Electric's XA/21 Unix-based system. This example demonstrates that consequences of correlated failure, which, although rare for high reliability systems, can be quite spectacular. *Therefore, it is important, when reasoning about system resilience, to take into account correlated component failure*.

Indeed, the effects of common-mode failure (CMF) have been studied extensively for software-based systems [20][21][22][23][24][25]. However, the systems studied are typically made up of only a few redundant components. In contrast to modelling software-based systems, many large networks have been studied by analysing graphical representations of the networks [11][12]. This approach is based on an assumption of failure independence between the network components. This assumption can be *difficult to justify* in many real world scenarios involving complex networks.

The CMF model [26] for a communication network illustrates the need for modelling failure correlation between the components of a complex network. The communication network is modelled as a set of connected routers in a directed network. Data packets are sent across the network via the routers and each router has a local buffer of fixed and finite capacity. The failure-rate for a given router is dependent on the flow of data passing through the router. However, because router failure affects subsequent data-flow across the network—data has to be sent via alternative routers— the failure of a router results in increased data flow through alternative routers. Therefore, under the assumption of dependence between router failure-rates and data flow, the failure-rates of these alternative routers are affected. A *Flow-Redistribution-Algorithm* was implemented to reroute flow across the network upon a path through the network becoming unavailable.

The model is realised as a *Stochastic-Activity-Network* (SAN) model with the Möbius tool [9]. Consequently, simulations of various scenarios can be run and a wealth of statistical data, including estimates for availability and reliability, can be obtained. The scenarios studied via simulation were both having *the same mean number of component failures*. The dependence of failure-rates on data-flow is modelled in scenario (a), but not modelled in scenario (b). The rate at which the network becomes unavailable due to component failure, is faster in scenario (a) than it is in scenario (b). This is because the dependence, enabled in scenario (a), implies that component failure tends to increase the data flow through the other system components, thereby increasing the "stress" on the other components. Consequently, the other components were more likely to fail and the system became unavailable more quickly. This is depicted in Figure 3**Error! Reference source not found.**, where the WD data is for the scenario with dependence modelled and the ND data is from scenario with failure–rate being independent of the flow.

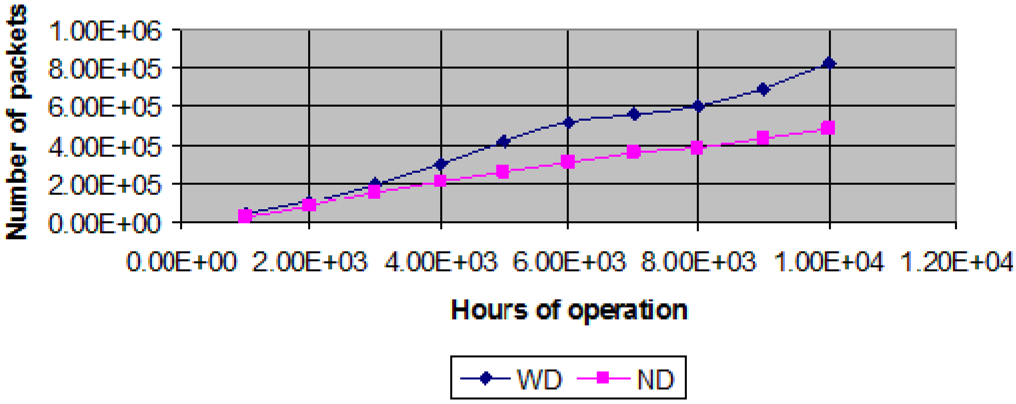



**Figure 3: Mean number of packets lost due to network unavailability**

## 2.3 Stationary vs. Dynamic Cascading Models—complex adaptive systems

The cascading models introduced in [28] reflect on models related to infrastructures, network robustness and vulnerability, introduced by the physics community [29][30][31]. Techniques from the area of complex adaptive systems have also been used to simulate infrastructures [76] [77]. Cranfield University is involved in research in this area and contributed to a workshop at Chatham House in 2004 [78]. Recent research into the resilience of supply chains is also relevant, as this is one way to model infrastructure interdependencies.

The vast majority of these models focus on the role of network topology while treating the redistribution of load as either time-independent or static. The load redistributions are instantaneous in the sense that they are adjusted to new situations in a non-continuous way. In order to demonstrate the importance of time-dependent adjustments of flows towards the new stationary state, following a network perturbation, we constructed two cascading models. The dynamic process adopted is a simple flow dynamics, based on a random walk in networks. This process allows us to derive equations for a *stationary* type of model:

$$c(\infty) = c^{(0)}(\infty) + (1-\tau)^{+} + j^{\pm}$$

and for a *dynamic* type of model:

$$c(t+1) = \tau c(t) + j^{\pm},$$

where $c$ is the nodal flow, $\tau$ is the matrix characterising the network and $j^{\pm}$ defines the capacities of source nodes and demands of sink nodes (more details about the derivation of these models can be found in [28]). In contrast to the stationary model, the dynamic model may be used to reproduce the transient effects in flow dynamics. A comparison of both models has shown that the discrepancy between the static and dynamic overloads, used to estimate the cascading effects, tends to be very pronounced. The static case was found to be systematically underestimating the network vulnerability. The difference in the size of the cascade can be sometimes larger than 80%. In addition, the role of exposure time (time needed for a link flow overload to disconnect the link from the network) on the dynamics of cascade propagation can be studied by these models. This simple dynamical approach provides additional insight into systems for which network topology is combined with flow, conservation and distribution laws. Examples of such systems are electricity networks or traffic systems.

# 3 Functional Models of Specific Networks

Three service-focused modelling methodologies have been developed within the IRRIIS project; the *Implementation-Service-Effects* (ISE) [32] model, *Preliminary Interdependency Analysis* (PIA) [27][33], and the *Stochastic modelling of interacting networks*. These approaches focus on the effects of dependence between services and how these effects manifest (e.g. service disruptions or increased security).

In sections 3.1 and 3.2 we discuss the application of both PIA and the Stochastic modelling of interacting networks to a network of services that were affected by a mini telecommunications blackout in the Rome area [33]. The Rome mini-telco black out (RMTB) occurred when, at a main telecommunications node in the Tor Pagnotta area of Rome [33], a metallic pipe carrying cooling water for the air conditioning plant, broke. The resulting flood led to several boards/devices failing due to short circuits and the main power supply going out of service. Diesel Generators, part of the Telco emergency power supply, failed to start due to the presence of water; only batteries provided power to the boards/devices still working; however eventually, the batteries dropped. Various services, including airport baggage handling facilities, postal services, and telecommunication services (both fix-to-fix and fix-to-mobile) in the Rome area were affected. In what follows, we describe two service-focused modelling approaches which have been applied to analyse this scenario.

## 3.1 Preliminary Interdependency Analysis

Some dependencies, with the benefit of hindsight, seem obvious upon discovering them. In the RMTB incident summarised above the proximity of the pipe to the Telecoms equipment (geographical dependency) implied that upon flooding there was an increased risk of components short circuiting. It would be useful to identify and ascertain the likelihood and impact of dependencies, such as this, quickly (similar to hazard identification in preliminary safety analyses. PIA [27][33] involves the relatively rapid identification of dependencies in a network of CIs. There are "easy wins" here since via PIAs dependencies can be identified quickly, including dependencies that are obvious once a sufficiently broad and relevant scope of the model has been systematically identified. Also, PIA addresses issues that arise when modelling CI, such as defining an appropriate set of entities to model, an appropriate level of abstraction for the model, and appropriate model boundaries.

PIA has been applied to the RMTB scenario resulting in both qualitative and quantitative analyses of the effects of various forms of dependence relevant to the scenario. For instance, resources that are shared between services may be a source of dependence between the services. The "strength" of the dependence, under different model parameterisations, can be studied by simulating variations in the state of the resource and observing the impact this has on the states of the dependent services.

Furthermore, to aid understanding and provide a basis for probabilistic modelling and Monte-Carlo simulation the service-level models obtained using PIA can be depicted as directed graphs. The graph nodes model CI entities such as services, assets and the environment, while edges/links between the nodes depict dependence relationships between the CI entities.

The stages in PIA include:

- **Scenario definition**: By detailing some event to be modelled (including relevant information about CIs, the systems and the processes thereof) the model scope is restricted;
- **Service level model definition and initial (inter-) dependency analysis**: Supported by the *Assurance and Safety Case Environment tool*, ASCE [6] this involves identifying model entities and dependence relationships between them;
- **Probabilistic modelling and interdependency exploration**: To explore possible effects of dependencies, Stochastic models of services are developed and simulated, using Möbius [7]. By using SAN models of the services, their relationships and (inter-) dependencies, we are able to study the frequency, duration and impact of rare, catastrophic events. Also, PIA is cyclical; a process of continuous model refinement is undertaken until a sufficiently well behaved model of the services is obtained. Consequently, the behaviour of the SAN models gives useful feedback for determining aspects of the service model that may need refinement.

Another example of the take up of light weight modelling techniques is ongoing work [121] to apply PIA in order to identify and explore dependencies a hospital Emergency Department has on other departments, and especially diagnostic services (pathology, radiology etc). The purpose is to identify safety requirements for safety cases for medical devices that are used in diagnostic services (such as laboratory analysers or radiology imaging equipment). The identification of dependencies will have an impact on the devices user interface design and on the format of test results printout in order to improve error detection where their output is used (i.e. the emergency department).

There are other approaches closely related to PIA. In our consultations (discussed in the main report of this study, [1]) we identified leading industrial practice using MODAF to describe high level qualitative modelling similar to the first phases of PIA.

Finally, there is work from computer scientists on applying discrete state models to infrastructures. For example, the work from the EU CRUTIAL project [45].

## 3.2 Stochastic models of interacting networks

Stochastic models of networks cover a broad field of models and tools that might be applicable to (inter-) dependency modelling. The events that have a high impact upon CIs are most likely to be rare events. A number of approaches to rare event simulation have been developed [97] [98][99] and have found application in finance and insurance risk [100], although further research is required to extend these methods to CI simulations.

In [34][35], a modelling methodology, based on a multi formalism and multi solution approach [36][41][42], was proposed to evaluate the service availability of interconnected networks. Service-availability of interconnected networks at time $t$ is intended as the probability of a service, delivered by a network, to be operational at time $t$, accounting the availability of each interconnected network required for service delivery. After the identification of a critical service, in turn, the networks which collectively provide such a service were identified and described in terms of topology, logical and physical paths, nominal failure and repair mechanisms of elements/segments, and mutual interconnections. Then, for each network, a different stochastic modelling formalism was adopted, looking at a convenient ratio between the formalism modelling power and its analytical tractability.

For demonstration purposes, this modelling methodology was applied to the RMTB scenario mentioned above. It focused on the availability of the public HDSL (High bit-rate Digital Subscriber Line) connection for the communication between the Main Control Centre (MCC) and the Disaster Recovery Control Centre (DRCC) of ACEA's SCADA system. Such a public connection traversed the flooded Telco node, referred in the above RMTB scenario. Such a node was powered by the ACEA power distribution grid; in the case of loss of the main power supply, the node was to be powered by a Telco emergency power supply, constituted by on-site battery benches (for short, intermittent main power interruptions) and diesel generators (for longer-term interruptions).

So, three interconnected networks had a major role on the availability of the HDSL connection: (a) the Telco network that directly supports the HDSL connection; (b) the Telco emergency power supply, which feeds the Telco network at different Telco sites and (c) the public power distribution grid (managed by ACEA) that provides the main power supply at the different Telco sites [35][39]. To represent and compute service availability of the above interconnected networks, a set of heterogeneous modelling techniques was deployed including Reliability Block Diagrams (RDB), a combinatorial method, implemented by a commercial tool [43] and Stochastic Activity Networks, implemented by Mobius, an academic tool [44]. In addition the NRA, Network Reliability Analyzer, a prototype academic tool, which implements algorithms based on Binary Decision Diagrams, a powerful formalism to manipulate Boolean expressions [33][46] was also used.

In Figure 4, some numerical results are depicted of the reliability of the pure HDSL connection of the *Telco network* in a number of different scenarios.

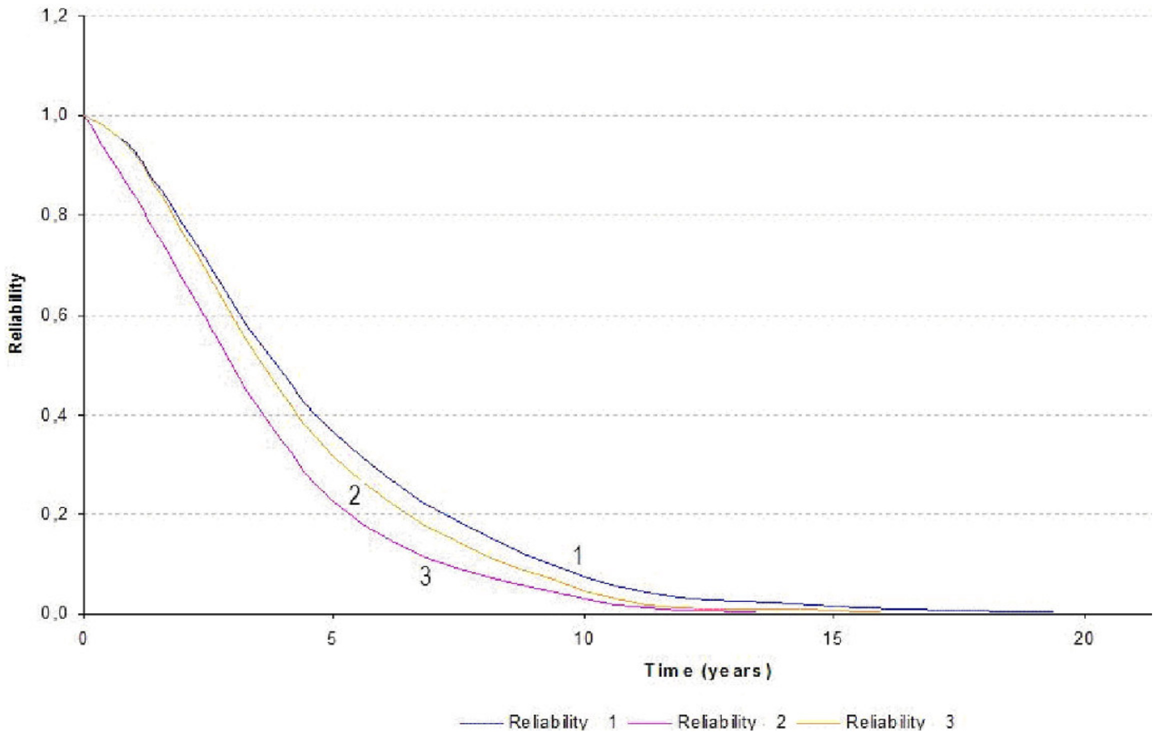



**Figure 4: Reliability of the HDSL connection**

Further data gathering and modelling efforts are on going to give a more complete numerical view of interdependencies among interconnected networks. Besides numbers, the novelty of the approach is in proposing a realistic methodology, that can help in reasoning on how and how much stochastic indicators of infrastructure interdependencies could change from a normal operative scenario (intended as definite CI topologies, CI interconnections, physical and logical service paths and nominal failure and repair mechanisms) up to any failure scenario, which could represent multiple failures and any consequences of deliberated attacks on the normal operative scenario. Failure scenarios could be obtained by forcing at the failure evidence each nominal value of parameters of the normal operative scenario.

# 4 Topological Analysis of Specific Networks

Many of the CI modeling approaches are based on network models that map the physical configuration of the components of a given system and their (physical or logical) interconnections [13]. The description of the topological properties of the network representing a given infrastructure can reveal useful information about system structure [47], evolutionary dynamics, topological vulnerability [48], and the level of functionality demanded of its components (for instance, topological *centrality measures* allow us to determine which network elements are likely to undergo intense usage because of their "location" in the network).

However, a simple topological description cannot capture all of the system's properties when some dynamical process, acting on the network, takes place. It has been shown that including the basic features of the dynamical process in the description of the infrastructure considerably increases the quality of the assessment which can be achieved. System vulnerabilities, for instance, can be studied in more detail by considering flows and their dynamics [28], more realistic time delays, or failure rates [49].

## 4.1 Evolution of Power Grid Topology

The construction of infrastructures such as an electrical power grid requires considerable resources and time. This process is influenced by many factors (for example, the economy, demography, energy prices, and technological development).

In [50] the growth of the French 400 kV transmission network topology is investigated. The analysed data set (see

Figure 5) describes the network evolution from its beginning in 1960 until the year 2000 in biannual time steps.

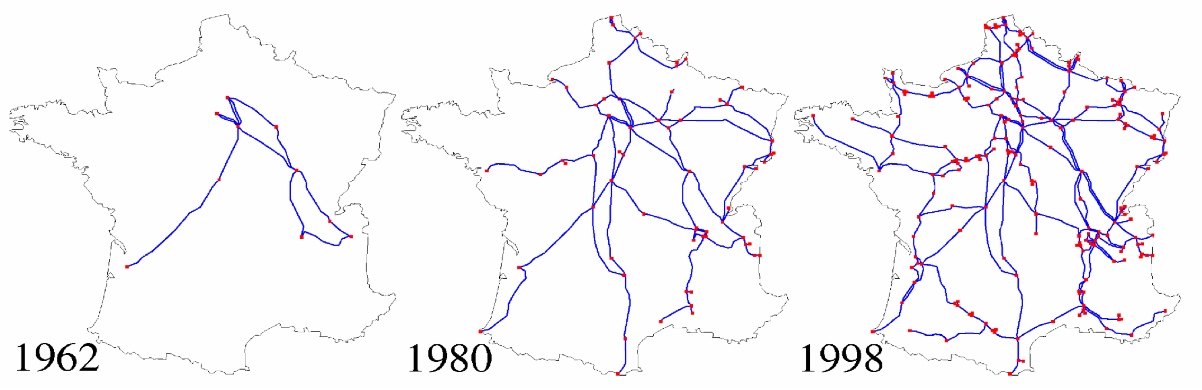



**Figure 5: Topology of the French high voltage electricity network for selected years**

The data analysis has been made in two stages:

1. Firstly, the growth process was analysed and found to be non-linear. Growth started slowly and was followed by very intensive growth which, finally, reached a phase of apparent saturation. Comparing this trend with indicators such as population, GDP, energy generation and energy consumption evolution, the closest similarity was found with the evolution of the nuclear power plants capacities, which are the largest source of electrical energy in France.
2. Secondly, the evolution of network's structural properties was analysed and in conclusion, it was found [50] that there is:
   - a constant mean node degree during the whole power grid construction process,
   - a small-world property appearing in the time when the network growth saturates,
   - a partial correlation between the position of multiple connections and "edge betweenness measure",
   - decreasing network sensitivity in relation to removal of links.

## 4.2 Vulnerability Assessment and Structural vs. Functional Properties of Networked Systems

Network research has dealt with the study of the effect of network topology on the functionality of the network itself. Although relevant results have been achieved in the case of electrical networks [51] and on interdependency effects between electrical and data-transport networks [52], a great deal of attention has been devoted to the study of the Internet [53][54][55], which is as this is a major CI and because its self-growing character enhances its interest from a basic-science standpoint. It has been shown [54][56] that the topology of the Internet AS-level routers can largely be reproduced by a growing process where both preferential attachment and clustering enhancement are simultaneously taken into account. Selective pressure on growth occurs on a *local* basis: new nodes are added to maximize (local) functionality (i.e the ease with which other nodes are reached) in a search for a Nash-type equilibrium, rather than to attain some global efficiency. Growth mechanisms with these characteristics can be used to generate networks with topologies that are strikingly similar to that of the Internet network (as mapped by ongoing projects [57][58]).

Synthetic networks (networks whose growth is described by growth models based on real data), can be used in simulation experiments to understand key differences between network topologies used to transport data. Traffic models, based on basic mechanisms [54] and an accurate reproduction of the TCP/IP stack [55], highlight the role of network hubs and their effects on transport mechanisms. From a structural point of view network hubs considerably reduce inter-node distances (with respect to random-type networks) and increase network resilience to random faults. However, from another perspective, the large *betweenness centrality* of hubs (i.e. they occur in a large number of shortest paths between the other nodes) transforms them into points of network weakness. In fact, buffers for the hubs start becoming full (thus refusing further connections) much earlier than other nodes with low centrality values. This is an example of the subtle interplay between structural and functional resilience: the same elements (the hubs) ensuring structural functionality are, at the same time, responsible of the system's weakness when data transport takes place.

Similar arguments hold for electrical networks. The topologies of several networks for electrical power transmission (high-voltage) have been analysed. The results of structural vulnerability tests (i.e. the assessment of which power lines are topologically relevant in terms of the damage produced if removed) have been compared to those of a functional assessment (i.e. the list of lines where most of the electrical power flows such that, if removed, create serious damage to the network and a need to re-dispatch a reduced amount of electrical power). It has been found that structurally relevant lines do not necessarily coincide with critical lines for the network's functioning underlining the importance of more complex modeling approaches that include explicit power flows [52].

# 5 Simulations

## 5.1 Introduction

Simulation is the imitation of some real thing, state of affairs, or process. The act of simulating something generally entails representing certain key characteristics or behaviours of a selected physical or abstract system [62]. The US DoD Modelling and Simulation Coordination Office defines 'simulation' as a "method for implementing a model over time" [63].

Simulation is often used as an adjunct to, or substitution for, modelling systems for which simple closed form analytic solutions are not possible. There are many different types of computer simulation; the common feature they all share is the attempt to generate a sample of representative scenarios for a model in which a complete enumeration of all possible states would be prohibitive or impossible.

Simulation is used by a number of different, but often related, communities including research and development, training and network management. The military in particular are interested in the development and use of simulation and synthetic environments for training, mission rehearsal and procurement. The communications network community have for many years used simulation for the design and management of networks. Risk analysis and the supply chain logistics communities are other examples.

Simulations may involve/immerse a human in real time, depending on the type of simulation and its goal. This could also be applied to CI simulation. Simulation for training environments is often referred to in the context of live, virtual and constructive simulations:

- Live simulation (where real people use simulated or "dummy" equipment in the real world);
- Virtual simulation (where real people use simulated equipment in a simulated world, or virtual environment), or
- Constructive simulation (where simulated people use simulated equipment in a simulated environment). Constructive simulation is often referred to as "wargaming" since it bears some resemblance to table-top war games in which players command armies of soldiers and equipment that move around a board.

So called live-virtual-constructive simulations combine any of these three approaches. The provision of live and/or virtual capabilities within CI simulation depends upon the stakeholder requirement for real-time analysis, decision support, disaster management and training.

There have been a number of previous reviews of CI modelling that include descriptions and analyses of simulation tools e.g. the US Idaho National Laboratory (INL) [40] and EU Integrated Risk Reduction of Information-based Infrastructure Systems (IRRIIS) project [71] reports.

The verification and validation of simulations is an important issue which has already been discussed in the main report [1].

## 5.2 Single domain/CNI sector simulators

A number of domain-specific simulation tools exist for communications, water and other sectors of the CNI as described in [40][71]. Some of the most popular tools include Opnet for communication network simulation [86] and Siemens Power System Simulation software for electricity network analysis [7]. On an assumption that the outages of the electricity grid have the greatest impact, the US Pacific Northwest National Laboratory (PNNL) have developed the GreenGrid tool [87] specifically for finding vulnerabilities in the electricity grid.

Communication network simulation is typically based upon a discrete-event modelling paradigm, as used in Opnet. The drive to develop more complex and accurate models has led to the development of hybrid approaches, combining discrete-event and flow methods [88].

When the infrastructure is modelled at a sufficiently high level of abstraction one simulation method may suffice (e.g. see the SAN work reported earlier ). Other examples include work by Nozick, et al which represents interconnected infrastructures through the use of networks (graphs of nodes and arcs) [95]. An example is given for interconnected gas and electricity networks, including the supporting information infrastructure (SCADA control systems). Simulation is carried out using Markov models to determine which investments, in more reliable equipment for example, have the greatest effect on improving system performance, subject to budget constraints on the total cost incurred. Nozick goes on to consider optimising the time to recover from a disruption using the same model [96].

## 5.3 Multi-domain simulation

The domain simulators mentioned above typically use methodologies that are specific and/or directly appropriate to the particular domain, e.g. discrete event modelling for Internet packet data transmission. By definition, infrastructure interdependencies analysis requires the ability of a simulation tool to be able to simulate multiple domains, or to be able to pass sufficient data between processes running in different simulators to be able to provide a useful (and valid) result. This is a key challenge for CI interdependencies research.

Other simulation tools exist, however, that are able to integrate multiple simulation approaches. The EPOCHS simulator [92] [93] was an earlier attempt to combine electric power grid and network simulation using available tools. EPOCHS uses software agents to coordinate message passing between the various simulators. One of the leading research tools in this area is the Ptolemy software framework [89], which has been developed specifically to research heterogeneous mixtures of models of computation.

The current version Ptolemy II includes the following models of computation; continuous-time modelling, dynamic dataflow, discrete-event modelling, finite state machines and modal model, process networks with asynchronous message passing, synchronous dataflow, synchronous reactive and wireless. Ptolemy II includes Vergil, a schematic editor. Based on Java, Ptolemy II is highly portable across different computing environments. Many Ptolemy II models will run within a web browser. Ptolemy has proved useful so far for the simulation of embedded control systems [90], sensor networks and many other types of system. In principle it could be used as a platform for research into multi-domain, multi-model approaches to infrastructure analysis. Ptolemy has also been extended by a number of projects, such as the Kepler project [91] for scientific workflows. Kepler workflows have been utilised by the Geosciences Network (GEON) [122] to develop a web portal to access large datasets, analysis tools and visualisation of earth sciences data. A similar approach could be adopted for infrastructure analysis, simulation and visualisation.

Research by New Mexico State University [94] proposes a framework for the integration and simulation of models from different engineering disciplines including industrial, civil, chemical and electrical. In [94], the approach with a sample scenario involving the structural collapse of a bridge and the releasing of industrial waste from trucks on the bridge during the collapse is illustrated (see Figure 6). The example combined a traffic flow model (discrete-event), a bridge stability model (static load) and a contaminant dispersal model (static and continuous-time).

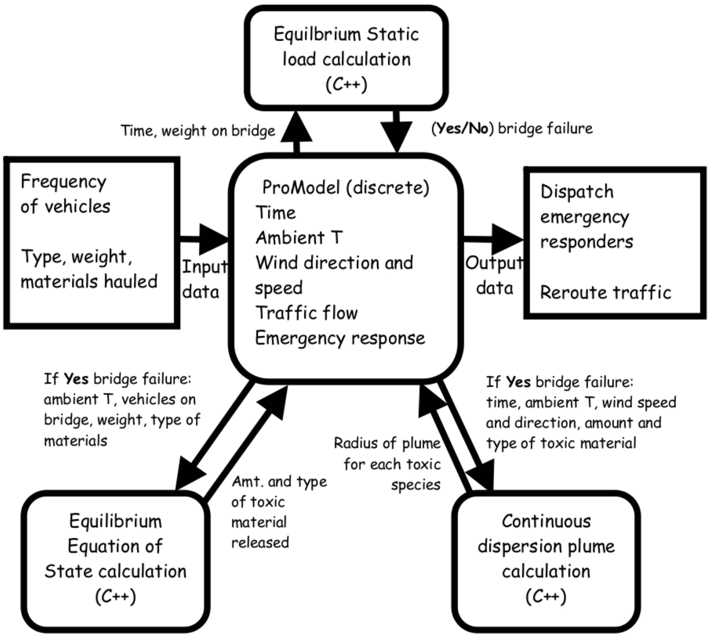



**Figure 6: Bridge collapse model (from [94])**

## 5.4 Distributed and federated simulations

The military commonly make use of federated simulation networks, including the high-speed secure US JMNIAN network. A summary of recent UK military simulation developments is provided in [101]. Such systems provide a real-time immersive environment, predominantly for training. NATO Project Snow Leopard is developing the NATO Education and Training Network, a live virtual, constructive training and mission rehearsal environment with live and synthetic forces [102].

Researchers and government agencies in the US have recognised the advantages of being able to federate disaster models from the Homeland Security domain to the Department of Defence (DoD) domain for disaster preparedness, response and recovery training and experimentation. The development of a federation between the FEMA HAZUS-MH model and the Consequence Management Simulation (CMSim) is described in [103]. HAZUS-MH is a risk assessment tool used for analysing potential loss due to natural disasters such as hurricane wind damage, and has 20,000 users. CMSim is a dynamic population model.

The federation of CIP simulations for information infrastructures is considered in [104], using software agents, and other research is reported in [105].

## 5.5 Simulation standards

Much of the current activity within the simulation research and development communities is related to the development of standards.

The 1516-2000 IEEE Standard for Modelling and Simulation (M&S) High Level Architecture (HLA) [106] provides rules for federated simulations. HLA is the successor to the Distributed Interactive Simulation (DIS), although DIS simulations may be run under HLA using the Real-Time Infrastructure (RTI), the middleware that supports federations, thus protecting the previous large investment in simulators for many organisations. [40]includes a summary of the advantages and disadvantages of HLA.

The Distributed Simulation Engineering and Execution Process (DSEEP) is intended as a high-level process framework for building and executing HLA federations and other distributed simulation applications.

The specification of scenarios is another key area currently under standardisation activities. The definition of what comprises a scenario is given in [123] as “A representation of the state, and present actions, of a set of animate and/or inanimate objects, so as to permit the exploration of, or reasoning about, their future state and the events that lead to it” .

The Military Scenario Definition Language (MSDL) is intended to provide a standard mechanism for loading scenarios independent of the application generating or using the scenario and is defined using an eXtensible Markup Language (XML) schema, having the advantage that scenario representations may be checked for conformance against the standard's schema.

The Simulation Reference Markup Language (SRML) promotes simulation engine specification, web-based simulation, and facilities delivery of models via the Web. OpenMSA, an open source community, is pursuing similar objectives.

## 5.6 Hardware and software requirements for simulation

High-fidelity simulation of thousands of infrastructure elements requires considerable computing power. Some simulators have been developed with the capability to simulate tens of thousands of network nodes (e.g. Qualnet [64]). This is possible using parallel computing technology. The US has invested in a supercomputer which has been used to run the CIMS application. DIS/HLA-based simulations using current

Commercial-Off-The-Shelf (COTS) network technology are typically limited to a few hundred entities. There are developments in Web-based simulation, such as SRML, which are aimed at supporting advances in grid computing.

# 6 Visualisation

As the name suggests, visualisation refers to the graphical representation of the modelling and analysis. This can be either on a standalone PC screen, or on large operating room screens, or over a set of various screen types, sometimes even distributed across various locations. Geographical Information Systems (GIS) are a typical example of visualisation. In interdependency analysis, visualisation tends to be layered, with several filtering options to guide decision support and communication.

Typical applications of visualisation include military command and control systems, medical visualisation, education, product development and market analysis.

As a discipline, visualisation focuses on helping people explore or explain data, typically through software systems that provide static or interactive visual representations [108]. The advent of scientific computing and advances in scientific and medical sensors has led to a growth in the visualisation of scientific and medical data.

When combined with simulation, visualisation can be a powerful tool for exploring real-world events. For example, to explore the state-of-the-art in high-quality visualisation of large-scale events a research team from Purdue University have produced an incredibly detailed finite-element model and visualisation of the September 11th, 2001 attacks [109].

### 6.1.1 Geographical Information Systems

Geographical Information Systems (GIS) are a key component in critical infrastructure modelling and analysis, and has a very wide variety of application, supporting all phases of the resilience lifecycle [126].

The US National Science Foundation (NSF) have defined GIS as “a computer-based system for capture, storage, retrieval, analysis and display of spatial (locationally defined) data”.

GIS data may be combined with, for example medical data, to predict disease outbreaks or bioterrorism attacks [127] or to identify critical assets that are within the inundation zone before or during a flood.

GIS has also been discussed in the main report of this study as one of the key capabilities. In this review, we restrict the discussion to visual analytics and associated challenges.

## 6.2 Visual analytics

The field of visual analytics is defined as “the science of analytical reasoning facilitated by interactive visual interfaces” and applies information visualisation techniques to the analysis and sense-making of data in order to derive insight, particularly from large, dynamic and possibly conflicting datasets [115]. Visual analytics is a growing area of Homeland Security research in the US and is relevant to critical infrastructure protection [116]. Visual analytics is, however, a new field with a number of research challenges.

In 2005, the US National Visualization and Analytics Centre (NVAC) published a roadmap for research into visual analytics in the field of terrorism prevention [115]. The report recommends research to advance the state of the art in four areas:

- The science of analytical reasoning techniques that enable users to obtain deep insights that directly support assessment, planning, and decision making
- Visual representations and interaction techniques that take advantage of the human eye's broad bandwidth pathway into the mind to allow users to see, explore, and understand large amounts of information at once
- Data representations and transformations that convert all types of conflicting and dynamic data in ways that support visualization and analysis
- Techniques to support production, presentation, and dissemination of the results of an analysis to communicate information in the appropriate context to a variety of audiences

The following extract from a recent lecture by Joseph Kielman of the US DHS Science and Technology Directorate provides further direction on the current research opportunities in visual analytics with application to homeland security [124].

- **Dynamic, on-Demand Data Processing and Visualization:** Capability for real-time management, analysis, and visualization of selected data in multiple forms and from multiple, diverse sources. These techniques would automatically select, rank, and correlate only those data relevant for purpose-driven decision-making.
- **Hypothesis-driven Analysis:** This capability would include three elements: automated retrospective analysis of collected or extant data using pre-selected hypotheses; automated generation of alternative hypotheses by constant updating of data; and prospective analysis of potential risks and threats using data-derived hypotheses.
- **Visualization of Structured, Unstructured, and Streaming Data:** Capability for integrated visual analysis of free text, database records, audio, video, imagery, transactional data, geographical data, and sensor information. The focus on this effort is twofold: development of a single, scalable framework for visual analytics and establishment and validation of reliable performance metrics for visual processing of data.
- **Mathematics of Discrete and Visual Analytics:** Development of the mathematical foundations for discrete processing and simulation and for visual analytics. This will provide a rigorous scientific basis for future algorithm development.
- **Scalable Filtering and Dissemination:** Techniques for secure, privacy-aware identification and dissemination of information among international, federal, state, tribal, and local agencies. This includes advanced methods, processes, and procedures that ensure sharing of information for immediate decision-making by multiple partners under a range of technical, political, and organizational parameters
- **Visualization and Simulation of Data:** Application of visualization techniques, discrete mathematics methods, and game theory to diverse

information, including development of new approaches to simulating multiple threats or disasters.

- **Mobile and Light-Weight Information Analytics and Sharing:** Information discovery, dissemination, and decision-making tools capable of being tailored for diverse homeland security applications and software architectures. These techniques need to focus on a range of law enforcement, public safety, public health, and emergency response applications.

Visual analytics have been applied to the study of vulnerabilities in electrical supply grids by visualising a grid in terms of its electrical properties [125]. This approach provides detection of network separation events that would otherwise result in blackouts.

## 6.3 Other challenges

The following is a non-exhaustive list of CI visualisation challenges:

### 6.3.1 Combining multiple datasets

Many of the benefits but also many of the challenges of visualisation lie in the combination of multiple datasets. Key to the success of a particular visualisation system is the underlying data. Even seemingly simple tasks, such as combining multiple satellite images into a single continuous image, or combining images with different resolutions, often requires a considerable amount of additional processing and often manual editing.

NISAC have developed the Fast Analysis Infrastructure Tool (FAIT) to determine infrastructure interdependencies from gathered data, including geographical and economic [128][129]. FAIT "utilizes system expert-defined object-oriented interdependencies, encoded in a rule-based expert systems software language (JESS), to define relationships between infrastructure assets across different infrastructures. These interdependencies take into account proximity, known service boundaries, ownership, and other unique characteristics of assets found in their associated metadata. Interdependencies are expressed in plain language and graphical (map) products [128]." An approach using a 'geovisualisation mashup' is described in [117].

### 6.3.2 Information visualisation

The requirement to visualise data that lacks a spatial domain or geometric structure has given rise to the field of information visualisation [130][131]. Information visualisation is typically concerned with abstract data structures, such as trees or graphs. Visualisation of computer network management or security data is one growing area [120].

The US National Institute of Health (NIH) and National Science Foundation (NSF) 2006 report on visualisation challenges focuses on scientific and medical visualisation and proposes the challenge of creating the 'Visual Google', a system that, while clearly not comprehensive and all-powerful, does help to enable non-experts to perform tasks otherwise beyond their capabilities in any reasonable time frame [108].

### 6.3.3 Interpretation of point cloud data

Infrastructure elements, particularly for virtual simulation, may use three-dimensional models of infrastructure elements, such as buildings. Such models may be captured using scanning methods, such as LIDAR (Light Detection and Ranging). Scanned data is typically in the form of large numbers of data points. This raises one of the challenges of visualisation for critical infrastructure protection. Scanned data, typically in the form of point clouds, must be related to physical surfaces, and surfaces to objects [118]. Tools are just starting to become available to carry out this conversion, albeit in a limited way.

# 7 Conclusions and summary

This document presents a review of research in infrastructure interdependency modeling and analysis. We aim to be sufficiently broad in order to illustrate the main avenues of current research and provide signposting to other reviews and related work. We have therefore done this by basing the review on the overall architecture of infrastructure interdependency modeling focusing on certain components of this architecture, namely interdependency analysis, infrastructure models and simulation and visualization. More attention is given to work specifically published as interdependency work and one glaring omission is work on the “intangible” or soft infrastructures.

The models and simulations developed to support infrastructure modeling and simulation are diverse and often complimentary. There are multiple ways in which these models are related and there is no single taxonomy or classification that suits all purposes. We might classify them according to:

- The communities from which they come e.g. the complex adaptive systems, dependability, security, stochastic modeling, Bayesian methods, and operational research. These are often exemplified by the different journals and conferences where the work is presented.
- The domains of application (power, telecommunications (telco), etc.).
- The underlying theories, the modeling frameworks and tools used, or the levels of abstraction. We have examples of very high level abstract models down to fine grain, high-fidelity realism. The same theories and techniques (e.g. Stochastic Activity Networks (SAN)) can be applied across many abstraction levels.
- The types of results that they produce, the time frame over which the models operate – from Milliseconds to years – and the resilience phase they relate to. We could use the resilience model that was presented in the main report [1] to speculate how the research might
    - reduce the frequency of failures;
    - increase the “inertia”/resistance of CI to perturbations;
    - reduce detection time;
    - accelerate decision time; and
    - reduce recovery time.

All of these provide different and useful perspectives. However, in this review we focus on the *results of the models* to provide a basis for describing relationships between the models. The classification of modelling activities considering the types of results they can provide is presented in Table 1 below. This includes:

- **Abstraction level and model boundaries:** Questions such as "how much of the real world should be modelled?" impact the modelling methodology and the applicability of modelling results. A continuum of possibilities exists, ranging from high-fidelity (very detailed) simulations to mid-range and low-fidelity models;
- **Technique and underlying theory:** (Inter-) dependency analysis of complex systems has been recognised as an inherently interdisciplinary activity. There exists a wealth of experience and knowledge from various domains relevant for (inter-) dependency modelling. This column in the table contains information about established formalisms, theory and techniques used as a basis for the models;
- **Model applicability:** The type of problems where the model can provide useful support is indicated in this column and the extent of tool support.

| | **Abstraction level** | **Theory** | **Applicable results and tools** |
|---|---|---|---|
| **Qualitative and semi-qualitative models** | *Model entities:* Varying from Mid to High level Nodes and links; Nodes (Systems or system components) and links (correlations, logical, functional or physical dependence)<br>*State Space:* Continuous or discrete, diverse | Continuous time Stochastic processes, Stochastic Activity Networks | Rapid dependency identification and analysis; Model scoping; Provides estimates for stochastic measures related to CI operation, including the likelihood of occurrence, extent, and duration of events in CI.<br>MODAF tools, ASCE, Möbius, and bespoke research software. |
| **Leontief-based model** | *Model entities:* Nodes (Systems or system components) and links (logical, functional or physical dependence)<br>*State Space:* Continuous, homogeneous | Graph theory, causal networks | Study of failure spreading behaviour; formulation and study of recovery strategies. Models of macro-economic loss.<br>Bespoke tools |
| **Indicative system dynamics models** | *Model entities:* Nodes (Systems or system components) and links showing influence<br>*State Space:* Continuous, homogeneous | System dynamics | Exploratory behaviour often at a high level of system behaviour based on dynamic models of how nodes interact. Often representing high-level services<br>Tools such as Gamma |
| **Topological and network models** | *Model entities:* Nodes (Systems or system components) and links (logical, functional or physical dependence) often generalised as | Graph theory, causal networks<br>Network topology and theories | Many examples of graph based models showing interaction of nodes.<br>Work on resilience of electricity networks using topological measures of risk |

| | Abstraction level | Theory | Applicable results and tools |
|---|---|---|---|
| | influence. Limited infrastructure functionality but detailed topology. | Systems dynamics<br>Computer science – FSA | and comparing these with functional measures.<br>A variety of tools and algorithms for finding topological properties of interest. |
| **Stochastic analysis of interacting networks** | *Service level, Nodes:* (at power side: primary and secondary substations; at telco side: ADM, Local Exchanges, Transit Exchanges)<br>*Links*: (at power side: electrical trunks; at telco side: optical rings, copper), Failure and repair rates<br>Also for Common-mode failure model can have higher level of abstraction<br>*Model entities:* Mid level<br>*State Space:* Continuous or discrete, diverse | Binary Decision Diagrams, Stochastic Activity Networks<br>Flow models, congestion modelling, Continuous time stochastic processes | Estimating stochastic indicators of the quality of service provided by interconnected, interdependent networks, including the likelihood of occurrence, extent, and duration of events in CI<br>ITEM, Möbius, NRA |
| **Generic cascading model, epidemiological models** | *Model entities:* High level Nodes (System Components) and links (structural, functional dependencies)<br>*State Space:* Continuous, homogeneous<br>High level, Complex networks | Dynamical systems, causal networks<br>Physics of complex systems, diffusion process in network | Study of cascading effects in complex networks; the influence of the transient effects for the estimated cascade size, the role of exposure time for estimation of cascade size.<br>Bespoke research models e.g. Java programming language; Touch-graph (open-source tool) |
| **High and mid fidelity simulation of multiple infrastructures** | The combines agents, discrete event simulation, 3D visualisation and scripting to investigate interdependencies and cascade effects within infrastructures.<br>Also federated simulations. | Co-ordination and scenario models via agent models and associated scripting<br>Various domain simulations (e.g. power grids, telco) often traffic or flow based | Provides direct examples of how infrastructures behave given a defined scenario.<br>The most extensive examples in deployed systems. See INL CIMS tool. Research is on simulation standards and agent based approaches<br>A number of generic agent based simulation frameworks are being developed (Cascadas) a well as muli-model frameworks such as Möbius, Ptolemy |

| | Abstraction level | Theory | Applicable results and tools |
|---|---|---|---|
| | | | There is also specific infrastructure modelling approaches. |
| **Domain simulations of single infrastructures** | This is a mature field with all domains having a variety of models | Physics and flow based models | Behaviour of a specific infrastructure. Only partially covered in review. |
| **Consequence models** | Plume and blast models, crowd models, models of economic impact | Physics based models | *Not included in review* |

**Table 1: Research review—summary of models**

The models presented in this review have different formulations and are amenable to diverse analyses. They can, however, be used for a common goal; to enhance our understanding of CIs and to contribute to improved system resilience. Improved system resilience can be achieved by targeted use of the modelling techniques and results at different phases during CI operation.

This research review offers a compact view on various modelling activities project. By discussing the contexts in which the model results are relevant we hope to have clarified and illustrated the relationships between them. The perspective obtained from producing this review is used in our judgments of the challenges described in the gap analysis in the main report.

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# 9 Glossary

| | |
|---|---|
| ACEA | Acea group of utility companies in Italy, http://web.aceaspa.it/acea/acea_eng/acea_spa/societa/index.html |
| ADM | Add-Drop Multiplexer |
| AgenaRisk tool | Bayesian network and simulation software used for risk analysis and decision support<br>Agena, http://www.agenarisk.com/ |
| ArcGIS tool | Integrated collection of GIS software products<br>ESRI, http://www.esri.com/software/arcgis/ |
| ASCE tool | 'Assurance and Safety Case Environment' |

| | |
|---|---|
| | Adelard, http://www.adelard.com/web/hnav/ASCE/index.html |
| CI | Critical Infrastructure<br>A critical infrastructure (CI) consists of those physical and information technology facilities, networks, services and assets which, if disrupted or destroyed, have a serious impact on the health, safety, security or economic well-being of citizens or the effective functioning of governments |
| CIMS | Modelling and Simulation framework developed in INL |
| CIP | Critical Infrastructure Protection |
| CMSim | Management Simulation |
| CNI | Critical National Infrastructure<br>Those key assets of the National Infrastructure (NI) the failure or loss of which could cause severe economic or social damage and/or large scale loss of life. |
| COTS | Commercial-Off-The-Shelf |
| CPNI | Centre for the Protection of National Infrastructure, see www.cpni.gov.uk |
| CSR | Centre for Software Reliability, City University London |
| CRUTIAL | Critical Utility Infrastructural Resilience, *EU project*<br>http://crutial.cesiricerca.it/default.asp |
| DHS | Department for Homeland Security, USA |
| DIS | Distributed Interactive Simulation |
| DoD | US Department of Defence |
| DRCC | the Disaster Recovery Control Centre (of ACEA's SCADA system) |
| DSEEP | Distributed Simulation Engineering and Execution Process |
| EPOCHS | A platform for agent-based electric power and communication simulation built from commercial off-the-shelf components |
| EPSRC | Engineering and Physical Sciences Research Council |
| FAIT | Fast Analysis Infrastructure Tool<br>NISAC, http://www.sandia.gov/nisac/fait.html |
| GA | Genetic Algorithm |
| GCM | Generic Cascading Models |
| GEON | Geosciences Network, see http://www.geongrid.org/ |
| GreenGrid | Set of tools used to determine and compare Data Centres' operational efficiency<br>GreenGrid, http://www.thegreengrid.org/ |
| HAZOPS | Hazards and Operability Studies |
| HAZUS-MH | Software product used to estimate the potential loss from disasters<br>FEMA, http://www.fema.gov/plan/prevent/hazus/ |
| HDSL | High bit-rate Digital Subscriber Line |

| | |
|---|---|
| HLA | High Level Architecture |
| IRRIIS | Integrated Risk-Reduction of Information-based, Infrastructure Systems<br>EU *project*, www.irriis.org/ |
| INL | US Idaho National Laboratory |
| PolyWorks | Point Cloud engineering solution<br>InnovMetric, www.innovmetric.com/ |
| ITEM | Reliability, Safety and Risk Assessment software tool<br>ITEM, http://www.itemsoft.com/ |
| JMNIAN | Joint Multi-National Interoperability Assurance Network |
| LANL | Los Alamos National Laboratory |
| LBM | Leontief-based model |
| LIDAR | Light Detection and Ranging |
| LLP | Limited Liability Partnership |
| Möbius tool | Software tool for modelling the behaviour of complex systems<br>http://www.mobius.uiuc.edu/ |
| MoD | UK Ministry of Defence |
| MODAF | UK Ministry of Defence Architecture Framework |
| MCC | Main Control Centre (of ACEA's SCADA system) |
| MSDL | Military Scenario Definition Language |
| Nash Equilibrium | In game theory, the *Nash equilibrium* is a solution concept of a game involving two or more players, in which each player is assumed to know the equilibrium strategies of the other players, and no player has anything to gain by changing only his or her own strategy unilaterally. |
| NIH | US National Institutes of Health |
| NISAC | National Infrastructure Simulation and Analysis Centre |
| NRA | Network Reliability Analyzer |
| NS-2 | a discrete event simulator targeted at networking research |
| NSF | National Science Foundation |
| NVAC | US National Visualization and Analytics Centre |
| OpenMSA | Open Modelling and Simulation Architecture, http://openssa.org/Home.html |
| Opnet | Network and applications management solution<br>Opnet technologies, http://www.opnet.com/ |
| PNNL | US Pacific Northwest National Laboratory |
| PIA | Preliminary Interdependency Analysis |
| Qualnet | High-fidelity network evaluation software that predicts wireless, wired and mixed-platform network and networking device performance |

| | |
|---|---|
| | Scalable network technologies, http://www.scalable-networks.com/index.php |
| RTI | Real-Time Infrastructure |
| RDB | Reliability Block Diagrams |
| RMTB | Rome mini-telco black out scenario |
| SCADA | Supervisory Control and Data Acquisition |
| SGI | Silicon Graphics Inc, www.sgi.com/ |
| SRML | Simulation Reference Markup Language |
| SNL | US Sandia National Laboratories |
| SAN | Stochastic Activity Networks |
| TCP/IP | Transmission Control Protocol/Internet Protocol |
| TSB | Technology Strategy *Board*, www.innovateuk.org/ |
| VRSim | US company that provides *data manipulation, visualization and interaction* tools and services, www.vrsim.net |
| XML | eXtensible Markup Language |

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