Chapter 4
Physical Simulators of Critical Infrastructures

**Antonio Di Pietro, Carlo Liberto, Nikolas Flourentzou,
Elias Kyriakides, Ivo Pothof and Gaetano Valenti**

Abstract Critical Infrastructures are an essential asset in modern societies and our everyday life is heavily dependent on their reliable and secure operation. The problem of controlling and managing critical infrastructures is becoming more and more difficult as they are increasing in size due to the growing demand for the services they provide and the geographical spread required. As these infrastructures become larger and more complex, fewer people understand how these networks work and the interactions between all the components. Thus, models are necessary so as to accurately predict their behavior under steady state or under failure/attack scenarios. This chapter provides a review on modeling and simulation approaches of critical infrastructures and in particular of electric power, telecommunications, water supply and drainage systems, and transportation systems.

A. Di Pietro (✉) · C. Liberto · G. Valenti
ENEA, Laboratory for the Analysis and Protection of Critical
Infrastructures and Laboratory of Sustainable Mobility, Rome, Italy
e-mail: antonio.dipietro@enea.it

C. Liberto
e-mail: carlo.liberto@enea.it

G. Valenti
e-mail: gaetano.valenti@enea.it

N. Flourentzou · E. Kyriakides
Department of Electrical and Computer Engineering and KIOS Research Center
for Intelligent Systems and Networks, University of Cyprus, Nicosia, Cyprus
e-mail: flourentzou.nikolas@ucy.ac.cy

E. Kyriakides
e-mail: elias@ucy.ac.cy

I. Pothof
Department of Industrial Hydrodynamics, Deltares, Delft, The Netherlands
e-mail: Ivo.Pothof@deltares.nl

R. Setola et al. (eds.), *Managing the Complexity of Critical Infrastructures*,
Studies in Systems, Decision and Control 90,
DOI 10.1007/978-3-319-51043-9_4

1 Introduction

Critical Infrastructures (CI) are the assets, systems, and networks, whether physical or virtual, which are essential for the functioning of a society and economy. Typical examples of critical infrastructures are electric power systems, telecommunication networks, water supply systems and transportation systems. These are dynamic, large-scale, complex, spatially distributed and data-rich systems. CI in urban areas deteriorate at an unknown pace, especially water, urban drainage and gas networks. Moreover, the damage to one of these systems, their destruction or disruption by natural disasters, terrorism, criminal activity or malicious behaviour, may produce a significant negative impact for the security and the wellness of citizens and being exacerbated by the existence of dependencies among different infrastructures [1]. For instance, an outage occurring in an electrical distribution network can produce disruptions for the telecommunication services which in turn may alter the normal functioning of banking services in a specific area thus causing negative effects for the citizens.

As CI are aging, interactions need to be accounted for in risk-based design, operation and management. However, many failure mechanisms associated with CI interactions are still poorly understood. To support the preparedness capability of CI managers and decision makers such as Civil Protection operators, modeling and simulation across CI has recently become a key field of study. For example, in pre-event times, an electric operator can run a power flow simulator on its power grid model to verify the feasibility of specific load shedding actions. Moreover, a water supply operator can simulate the behavior of its water network and verify management strategies for improving the water quality throughout the network. During post-event times, simulators may be used to implement allocation policies or resources (e.g., electricity, water) or to improve response readiness of emergency transportation facilities such as fire engines, fire trucks, and ambulances to reach the disaster areas.

In several EU countries the pace with which infrastructure is rehabilitated implicitly assumes that the technical lifetime is between 120 and 800 years. Clearly this is unrealistic. Due to ageing, the functionality gradually decreases, while the underlying processes and interactions between individual infrastructures are largely unknown. This, combined with a growing pressure on these infrastructures (climate change, 82% of the population in EU living in urban areas by 2050), is requiring to increase our understanding of all processes involved along with the development of engineering tools for (re-)design.

There are several ways that can be utilized to model critical infrastructures, including network flow models, system dynamics models, agent-based models, or combinations of these models. These modeling methodologies are used in commercial or research-based "physical simulators". These are tools that try to mimic the behaviour of a system. They can be deterministic or stochastic, continuous time or discrete-time based or being based on differential or software agents. In this chapter, the focus is on simulators that can reproduce the behavior of the major critical infrastructures by analyzing the kind of data they require and produce and thus on the benefits they can provide to the different end users.

This chapter provides a summary of some of the main tools used for modeling critical infrastructures. Clearly, the list is non-exhaustive as there is a large number of commercial or research-based physical simulators in use today.

2 Power Systems

At the epicenter of the well-being and prosperity of society lie the electric power systems. Contemporary power systems are operated under heavily stressed conditions due the ever increasing electricity demand and deregulated electricity market. Maintaining the reliability and security of the power systems under such stressed conditions is challenging. The occurrence of severe faults and disturbances in the system needs to be detected timely, and necessary actions need to be taken.

In order to prepare for faults or unexpected load changes, power system operators assess the stability of the power system by examining offline several scenarios. The transient analysis that is usually used in the power system control center enhances the situational awareness of the power system operators by providing a visualization of the generator rotor angles, bus voltages, and system frequency during large contingencies. Therefore, operators can plan a set of remedial measures to maintain the stability of the system.

The electrical power system is typically divided in three main sections: the Generation in large power plants, the long distance Transmission network, and the Distribution grid. There are several software applications which study the power system and its multitude of components. Some of the most used physical simulators for power systems are described in this Section.

2.1 DIgSILENT PowerFactory

PowerFactory [2] is a solution for modelling and analysis of generation/transmission/distribution/industrial grids, overall functional integration, and data management. It offers a complete suite of functions for studying large interconnected power systems integrating new technologies for power generation and transmission such as wind generation, virtual power plants, HVDC-VSC or FACTS. PowerFactory's functions can be applied to improve the security, stability and economics of complex power transmission systems.

PowerFactory provides comprehensive modelling features for studying all kinds of phasing technologies, meshed or radial topologies and railway supply systems connected to public distribution systems. In order to reduce network unbalance, improve quality of supply and optimize distribution networks, PowerFactory offers multi-phase power flow analysis, short circuit analysis (IEC 60909, ANSI C37 and multiple fault analysis), harmonic analysis, time-domain simulation and reliability assessment. Other standard features include the modelling of distributed generation and virtual power plants, voltage drop analysis, branch loading calculation, daily load curves and the consideration of LV load diversity. This is complemented by an easy-to-use protection coordination wizard.

Industrial power systems supplying refineries, paper-mills, car factories or other plants with high power quality requirements benefit from high precision PowerFactory power flow algorithms, short circuit calculation features, four-wire modelling, harmonics-analysis and filter design options.

PowerFactory can also be used for analyzing the impact of distributed generation on the network. It combines classical distribution system analysis functions, such as voltage drop calculation, unbalanced network, load and generation modelling, and selectivity analysis.

DIgSILENT StationWare provides a reliable central protection settings database and management system for the complete power system substation data, both to manage the various control parameters and to centrally store substation related information. StationWare is based on the latest .NET technology.

DIgSILENT PowerFactory Monitor (PFM) is a multi-functional Dynamic System Monitor which fully integrates with DIgSILENT PowerFactory software. The PFM features grid and plant monitoring, fault recording, grid characteristics analysis by offering easy access to recorded data, analysis of trends, verification of system upset responses and test results.

2.2 SIEMENS PSS® E

PSS E is a fully-featured software for electrical transmission system analysis and planning. It provides integration into clients' workflow (through built-in Python® API) for automation and customization. PSS E provides comprehensive modeling capabilities for enabling sophisticated analyses and accuracy. It anticipates network problems and analyzes alternatives. It calculates the area exchanges in the power network planning. PPS E is used by transmission planners, operations planners, consultants, and research communities.

PSS® MOD is used for Project Modeling and Data Management, which is specifically designed for PSS E. The user can manage a great number of change cases for PSS E. PSS MOD assembles sets of model changes into "queues". Queues can then be managed and organized in various fashions depending on the needs of the PSS E user. Queues are coupled with PSS MOD seasonal and annual profiles to provide the PSS E user with a procedure for organizing and reorganizing system investigations. All this without the need for generating a great number of PSS E base cases, or repeatedly rerunning PSS E cases when planning sequences change.

2.3 SIEMENS PSS$^{®}$ SINCAL

The SINCAL platform offers a full set of calculation modules based on a single database “all-in-one”, and optimized GUI for specific tasks. SINCAL is used for the complete simulation and easy evaluation based on commercial databases, for real-time simulation, for the management of protection devices, and for workflow-driven system planning.

SINCAL provides a complete range of modules for design, modeling and analysis of electrical power systems as well as pipe networks; gas pipes for calculations for different pressure levels, water pipes for steady-state, dynamic and water tower filling calculation, and district heating and cooling pipes for calculation of flow and return flow.

SINCAL offers a comprehensive range of analysis modules and tools facilitating the planning, design and operation of power systems. Its field of application ranges from short-term to long-term planning tasks, fault analysis, reliability, harmonic response, protection coordination, stability (RMS) and electromagnetic transient (EMT) studies.

SINCAL supports all types of networks from low to the highest voltage levels with balanced and unbalanced network models e.g., four wire systems or transposed systems with the full coupling matrix. It can be used for cost analysis of future scenarios as well. Several analysis modules, such as protection or dynamic simulation, are also ideally suited for training purposes.

2.4 SIEMENS PSS$^{®}$ NETOMAC

NETOMAC is designed as a single program for facilitating access to and manage tasks associated with the dynamic phenomena of electrical power networks. It links up the most important methods for the analysis of dynamics of electrical networks in the time and frequency domains. The NETOMAC key features of the tool offer:

- Simulation of electromagnetic and electromechanical transient phenomena in the time domain and frequency range analysis;
- Steady-state load-flow and short-circuit current calculations;
- Optimization and eigenvalue analysis;
- Real-time simulation for protection testing, network security calculations;
- Simulation of torsional vibration systems;
- Parameter identification and reduction of passive/active networks;
- Interactive network training simulator and extended user interface for the graphical input of network and controllers structures and results documentation;
- Data import from other planning packages (e.g. PSS$^{®}$ E, PSS$^{®}$ SINCAL) and additional formats for data export.

The NETOMAC program system presents a multitude of possibilities for simulating all electromagnetic and electromechanical phenomena in electrical systems. The analysis in the frequency domain usefully supplements the processing possibilities. The eigenvalue analysis opens up numerous methods leading further, such as the establishing of dynamic, reduced network models by reducing the order.

Many kinds of pre-processing are available, such as parameterizing of power lines or motors and identifying of model parameters. The possibilities of system analysis are supplemented by user-defined optimizing processes.

NETOMAC links up the most important methods for the analysis of dynamics of electrical networks in the time and frequency domain. It is a program for all tasks associated with the dynamic phenomena of electrical networks. It presents real-time capability for protection testing and network security calculations thus providing fast response when network problems occur.

2.5 MATLAB® Simulink®

Simulink is a block diagram environment for multidomain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems. Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB, enabling to incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis.

Simulink is used by industry, research communities, for real-time experimental verification and for educational purposes.

Key Features

- Graphical editor for building and managing hierarchical block diagrams;
- Libraries of predefined blocks for modeling continuous-time and discrete-time systems;
- Simulation engine with fixed-step and variable-step ODE solvers;
- Scopes and data displays for viewing simulation results;
- Project and data management tools for managing model files and data;
- Model analysis tools for refining model architecture and increasing simulation speed;
- MATLAB Function block for importing MATLAB algorithms into models;
- Legacy Code Tool for importing C and C++ code into models.

2.6 PowerWorld Simulator

PowerWorld is an interactive power system simulation package designed to simulate high voltage power system operation on a time frame ranging from several minutes to several days. The software contains a power flow analysis, voltage control, generation control and area interchange, contingency analysis, linear sensitivity analysis, and fault analysis.

The Simulator includes the following features:

- Intuitive, User-Friendly GUI
- Model Explorer
- Solutions Options
- Presentation Tools
- Interactive, Animated Diagrams
- Contingency Analysis
- Geographic Information Systems
- Time-Step Simulation
- Automated Diagram Creation and Modification Tools
- Compatibility
- Modeling Capabilities
- Sensitivities
- Area Generation Control
- Difference Flows
- Contoured Displays
- Script Actions
- Customer Support

PowerWorld is a tool for system planning and operation technicians, engineers, electricity market analysts and managers involved in power system network analysis. It is used by the energy industry to enhance the customer experience. It is also suited for research and teaching power systems operations and analysis.

2.7 PSCAD™ EMTDC™

PSCAD is time domain simulation software for analyzing transients in electrical networks. It can simulate control systems and complex networks by managing data in a completely integrated graphical environment. It solves differential equations of the power system and controls in the time-domain. The results are computed as instantaneous values in time but can be converted to phasor magnitudes and angles by the true RMS meters and/or FFT spectrum analyzers.

PSCAD is a collection of programs, providing a graphical Unix-based user interface to electromagnetic transients program. EMTDC is an integral part of

PSCAD as it is the library of power system component models and procedures, which establish the simulation software provided with PSCAD.

EMTDC (with PSCAD) is used by engineers and scientists from utilities, manufacturers, consultants, and research/academic institutions, all over the world. It is used in planning, operation, design, commissioning, tender specification preparation, teaching, and advanced research.

PSCAD performs evaluation of switching transients and harmonics generated by static converters and analyze over-voltages, instabilities and non-linearities in a power system. It examines transient effects of distributed generation and Sub-Synchronous Resonance.

E-Tran is a software program which gives additional capabilities to PSCAD. It allows a direct translation of Power System Simulator data into PSCAD, while the complete model can be represented graphically. It has data entry based on the same per-unit system and data entry standards as used in loadflow programs. An E-Tran add-on (which allows large PSCAD cases to be broken up and run using parallel processing on multiple cores or on multiple computers) achieves significant reduction of the simulation runtime.

2.8 EMTP-RV

EMTP is a computational engine for the simulation and analysis of electromagnetic, electromechanical and control systems transients in multiphase electrical power systems. It can be used to investigate grid integration of wind generation units, and to analyze and control power electronics for power systems. EMTP provides solutions to coordinate insulation for large networks. It provides protection features associated with power oscillations and saturation problems. It analyzes ferroresonance, shaft torsional resonance stress, and studies synchronous machines control and excitation.

EMTP is used by the industry, engineers and research communities, and for educational purposes to give a first experience on the simulation and analysis of power systems transients.

3 Telecommunication Networks

Telecommunication simulators can be used to verify analytical models, evaluate the performance of new protocols, or to test the security of the networks against cyber attacks. Most of them are based on the Discrete Event Simulation (DES) engine and allow to model the behaviour of a network (e.g., a local area network or LAN) by calculating the interaction among components (e.g., hosts, routers, data links, packets). When a virtual network component is used in conjunction with live applications and services, this mechanism is also referred as network emulation. In the following, we focus on ns-2, the most common network simulator that targeted at networking research. Further, we list the main functionalities of other simulators.

3.1 ns-2

ns-2 [3] is a public domain event-driven network simulator developed at UC Berkeley. It is available on different platforms such as UNIX, Free BSD and Windows OS platforms. ns-2 provide simulation tools including result display, analysis and converters to simulate small-scale networks.

It can simulate of a variety of IP networks and applications such as (TCP and UDP implementation, traffic source behaviour such as FTP, Telnet, Web, CBR and VBR, router queue management, routing algorithms such as Dijkstra and multicasting and some MAC layer protocols for LAN). ns-can accept three different languages to code the network: (i) Tcl, which is used to write simulation scripts; (ii) OTcl, to define the event-scheduler and indicate the traffic sources when the traffic starts and stops; and (iii) C++, to implement the schedulers and network components.

Figure 1 shows Nam, an animation tool for viewing network simulation traces and real world packet traces that can be used to analyze ns-2 based network evolution through a simulation. Nam supports topology layout, packet level animation, and various data inspection tools.

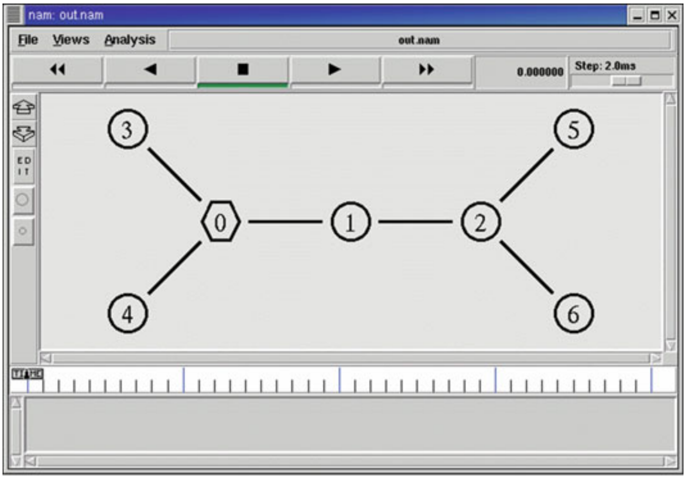

Fig. 1 Simulation topology

3.2 Other Simulators

OMNET++ [4] provides a set of high-level communication protocols and provide additional features to develop complex IT systems, queuing networks or hardware architectures. OMNET++ includes: (i) a graphical network editor (GNED) to allow graphical topology build; (ii) a simulation kernel library containing definitions of objects used to create topologies; (iii) a compiler for the topology description language; (iv) a Graphical and command-line interfaces for simulation execution; (v) Graphical tools for results analysis; (vi) a model documentation tool to create dynamically documentation on the created model.

iSSFNet [5] network simulator relies on common API for parallel simulation of networks, the scalable simulation framework (SSF). Based on iSSFNet, a network viewer module of the simulation environment (RINSE) allows to have different views of the simulated network as well as to execute commands such as attacks and defenses commands and try specific countermeasures to preserve the services delivery of the network.

OPNET [6] allows the analysis and design of a communication network, the devices, protocols, and applications used. OPNET allows to analyse simulated networks to compare the impact of different technology designs on end-to-end behaviour and incorporates protocols and technologies. In addition, it includes a development environment to model specific network types and technologies including VoIP, TCP, IPv6, etc.

4 Water Networks and Urban Drainage

The following phases are recognized in the life cycle of a pipeline system (see also the Dutch standard NEN-EN 3650 ‘Requirements for Pipeline Systems’): (i) Design; (ii) Construction and commissioning/testing and (iii) Operation and maintenance (O&M).

Before the design, the development stage takes place, also known as the preliminary design. The preliminary design is mostly determined by the usage requirements (functional requirements) and planning aspects. The design phase can be divided into the basic design and the detailed design.

In the basic design, the definite points of departure (schedule of requirements) for the design are determined. In the detailed design, the calculations, drawings and specifications are established for the realisation and operational management stage. There is no clear distinction between the two design stages and, in this section, it is summarised as ‘design’. The design of water infrastructure is an iterative process consisting of the pipeline design/network layout, design of pumping stations and other main components, design of surge protection devices and control strategies and finally the design of monitoring instrumentation and incidental O&M procedures [7]. Iterations in these design steps may be required for various reasons. For example, the surge protection may become so expensive that a slightly larger pipe diameter or other pipe routing may lead to a more LCC-effective system. Another reason for iterations in the design steps is the fact that the engineering team needs to find a balance between conflicting criteria, such as a short residence time in a drinking water network, leading to selection of small diameter pipes, versus minimum pumping costs, leading to larger pipe diameters. The final system design is affected by many of these conflicting technical and non-technical criteria.

Physical simulators are mainly used to support the iterative decision processes during the design and O&M phase of water supply and urban drainage systems. Physical simulators are used to a lesser extent during the construction/commissioning phase. The overall fundamental objective of using physical simulators for water infrastructure is to support decision making to obtain an acceptable serviceability level at acceptable societal life cycle costs. One could start a philosophical discussion on replacing the words 'acceptable' by 'minimum', but I have chosen 'acceptable' on purpose. The subsections hereafter will address the main topics for which physical simulation tools are used in these three life cycle phases.

4.1 Design Phase

Physical simulators serve different but very similar purposes for drinking water infrastructure and urban drainage infrastructure, as illustrated in Table 1 hereafter. Furthermore, this table summarises what kind of simulator functionality is required to verify the specific design criterion.

Table 1 shows that physical simulators can be used at three different time scales. The basic lay-out of the infrastructure can be determined with steady state modeling approaches, while most detailed design questions demand for so-called extended period or slow transient simulations spanning typically one or two days. Simulation at these time scales can be applied to large distribution networks, including all pipe components down to the level of the individual property owner. Most of the simulation models, addressing this time scale, can be transferred from the design phase to the O&M phase and are being used in day-to-day operations of the water infrastructure.

The full transient simulation models include pressure wave propagation phenomena in pressurized systems. Full transient models are computationally much more expensive that slow transient models. These models are used for a wide variety of emergency conditions and have typical simulation time horizons of a few minutes up to 24 h, depending on system size and design question. It is generally not necessary to run a full transient model on a complete all-pipe network lay-out, although the current computing power is getting strong enough to do so.

Since the water infrastructure is getting more and more automated to save energy and other operational costs, the design of normal control systems is verified in more detail nowadays than a couple of decades ago. The design of these control systems needs to be evaluated in full transient mode, because the pressure wave propagation

Table 1 Overview of design criteria and physical simulator requirements for water infrastructure

Generic design criterion	Water supply	Urban drainage	Physical simulator functionality
Hydraulic capacity	Design flow demand distribution. Max flow rate	Maximum stormwater run-off. Max. domestic inflow in separated system	Steady state
Pressure, Water level	Normal operating pressures within limited range, typically 2–6 barg in distribution networks	Water levels below ground level (no flooding) and no combined sewage overflow for regular run-off conditions	Slow transient
Water quality	Residence time acceptable, chlorine concentration (if applicable)	Limited residence time to limit biological decay. Sufficient local velocities for solids transport	Slow transient
Extreme pressures during emergency conditions	Power failure, Emergency valve closure, start/stop procedures, etc.	Power failure in pressured wastewater systems	Full transient
Robust automation	Emergency control systems, normal control settings	Sewerage networks generally have very limited controls, but pressurised wastewater systems have similar complexity as water supply systems w.r.t. control	Full transient

in pressurized (waste) water networks interferes with the operation of the control systems [8]. Furthermore, emergency control systems are used in combination with anti-surge hardware and may reduce investment costs for the anti-surge hardware significantly [9]. Similar simulators are not only used for the hydraulic design of the water networks and transmission systems, but also for the hydraulic design of treatment facilities [10].

Physical simulators of water infrastructure are used as a verification tool to test whether all applicable criteria are accomplished. Many simulators have built-in optimization routines to further support the design and decision processes, for example to select optimized pipe diameters or to find a minimum required surge vessel volume that satisfies the transient criteria on minimum pressures and water levels.

4.2 Construction and Commissioning Phase

Most of the water infrastructure is built with trenched installation techniques, for which physical simulators are not required. Very dedicated simulation tools are being applied for specialized installation techniques such as horizontal directional drilling (HDD).

The commissioning phase of water infrastructure, especially large pumping stations, can be supported with physical simulators, especially in situations in which the design scenarios cannot be clearly replicated during site acceptance tests (SAT). Many practical issues may lead to deviations between design and commissioning. Two examples are listed: (1) A new pumping station connected to an existing network; (2) a new wastewater pumping station which is designed for a certain future flow rate, which cannot be delivered immediately after construction. In these situations, the commissioning can be performed with temporary system modifications to accommodate the design flow or the commissioning can be performed under part-load conditions. Both approaches for the commissioning phase need physical simulators for model calibration and for extrapolation of commissioning results to design scenarios. Physical simulators, typically full transient models, are also used to set-up the commissioning tests in situations where temporary system modifications are required to perform site-acceptance tests.

4.3 Operation and Maintenance (O&M) Phase

The physical simulators that have been for design are used in the O&M phase as well in a similar off-line mode. Typical activities which are supported by physical simulators include:

(1) Redesign of existing infrastructure;
(2) Debottlenecking to mitigate a performance loss;
(3) Temporary modifications to support maintenance operations (e.g. flushing of a drinking water network, replacing pipe sections in a water network, etc.);
(4) Troubleshooting to analyze incidents, like a water quality complaint or pipe burst.

An emerging field is the real-time coupling of physical water infrastructure simulators to the existing SCADA systems. In this way, the simulation model is used as an advanced and spatially detailed instrument to measure the primary processes in the water infrastructure. Such a model will be helpful for troubleshooting activities, since the real-time model performance can be analyzed after an incident has occurred. Furthermore, if the model is calibrated in an automatic way, performance loss can be detected in an early stage. The real-time integration of measurements and physical modeling results, combined with clear performance indicators has proven to be very valuable for the operation and maintenance scheduling of complex pressurized wastewater networks [11].

These kind of model-data integration applications are necessary for the further development of Model-Predictive-Control (MPC) strategies in water supply and urban drainage applications. Historic data analyses are widely used in the operational control of water distribution networks and urban drainage systems. MPC is the next step to further improve the performance of the existing water infrastructure.

It is anticipated that physical simulators at different temporal and spatial scales will be required for MPC applications.

Finally, other simulation tools are used to support decision making on replacement, refurbishment or renovation works [12, 13]. So far, these Asset Management simulation tools have not been included, since the focus of this section was on the primary processes and not on deterioration processes of the infrastructure and its surroundings.

5 Transportation Systems

Overall concept

Urban street networks are increasingly susceptible to unplanned disruptions triggered by extreme natural phenomena or man-made emergencies including traffic accidents of high severity. Efforts to address this challenging issue, leading to high social and economic losses, are needed to increase network ability to absorb the consequences of disruptions in the face of adverse events.

There is thus a pressing need to assess network vulnerability, that is to understand how a street network and its functionality might be impacted when subjected to disruptions [14, 15, 16]. Vulnerability measures based on distance are more suitable for sparse regional networks since drivers may need to take longer detours to reach their destinations in case of link disruption [17]. By contrast, in dense urban network where many alternative routes may be available drivers often prefer quicker routes which need not necessarily be shorter in terms of distance. For this reason, time-based approaches to studying vulnerability are more appropriate in high traffic density urban areas.

Vulnerability analysis provides valuable insights to facilitate the development of suitable responses to possible crisis situations and to properly prioritize investments for developing network resistance to disruptions. Basically, each component of a network contributes with a different weight to the vulnerability of a network and that weight could change through time, within a day or day-by-day, mostly due to travel demand fluctuations.

Immediately after a network disruption, drivers are forced to explore the network and modify their travel behavior according to their travel experience and reliance on the available information sources. The main options that the drivers can do are to change their normal route, to postpone their trips, to switch to alternative travel modes or to satisfy needs at other destinations.

However, the modeling of driver reaction to major network disruptions presents some methodological challenges, both in describing the day-to-day route choice process and in assessing its confidence and compliance with received information to adapt its behavior. A further modeling difficulty comes from the extensive and expensive data collection efforts needed to capture attitudes and perceptions that shape their day-to-day travel decisions.

In scientific literature, many studies have been conducted to identify and evaluate weakness points of a network, where link closures are likely to occur, and where the impacts would be the most severe. Some analytical approaches have been proposed to find structural weaknesses in the network topology, neglecting network-wide impacts on travel demand in terms of congestion and negative externalities [18–22].

Further approaches have been conducted by using traffic assignment technique that allows to simulate how Origin-Destination (OD) travel demand loads the links of a network when road closures occur [15, 16, 23].

An OD Matrix is traditionally determined through the costly procedure of conducting OD travel surveys in the study area usually conducted once in every one decade and by the time the survey data are collected and processed, the OD data obtained become obsolete. Alternatively, an OD matrix can be estimated by using traffic counts on links and prior OD flow estimations to guide the solution procedure.

Traffic simulation models have also become a useful tool for studying how candidate alternate routes can accommodate traffic diverted when disruptions occur. Current simulation techniques range from microscopic models, capturing the behavior of vehicles and drivers in much more detail thus providing a more comprehensive representation of the traffic process, to macroscopic models tending to model traffic of large networks, in lesser detail, as a continuous flow often using formulations that are inspired by gas-kinetic or hydrodynamic equations.

Traffic simulation models can also be broadly categorized as static and dynamic models. The former focuses on long-term, steady traffic states, while the latter focuses on short-term, dynamic traffic states. Compared to static models, dynamic traffic models have a more realistic representation of traffic flow, and a more detailed representation of the traffic system.

However urban traffic networks are usually really complex systems with a large number of vehicles, many road sections and intersection points often with conflicting traffic flows which can result in a large amount of congestion. Consequently, only sophisticated dynamic simulators are well suited to urban environments where demand greatly varies over time and large fluctuations in travel times occur as a result of congestion, queues that build up and dissipate, and so on. Furthermore calibrating a complex traffic simulator is time-consuming process that requires extra care to adjust capacity, demand, and behavior parameters so that field-observed traffic data can be well-approximated.

In the following, we analyze in detail an analytical simulation tool called FIRST (TraFfic AnalysIs in EmeRgency Situations Tool) to model and measure vulnerability within dense urban networks, to estimate the impact area caused by traffic disruptions and to determine possible diversion routes around the closed streets.

A key novelty of our simulation tool is that we use a large amount of Floating Car Data (FCD) to derive, in a cost-effective way, the travel and traffic patterns in a urban area in terms of OD relations, route choice information, congestion levels and travel times. Our framework thus combines topological properties of a network, including basic traffic rules, with patterns of road usage and OD locations of the drivers throughout a day extracted from FCD. FIRST uses a comprehensive street network database including geometry and attributes that are needed to identify sound traffic diversion strategies around disruptions. FIRST utilizes heuristic approaches to estimate the OD of the traffic on the closed links and to reassign the estimated OD to the remainder of the network to find alternate routes for traffic diversion.

The vulnerability metrics and the simulation of disruption scenarios was applied to the case of the street network of Rome using FCD collected by an extensive sample of privately owned vehicles currently reaching a penetration rate of around 8%.

Description of the traffic simulator

FIRST is a software tool designed to assist decision makers in strengthening urban street network resilience against traffic disruptions triggered by extreme natural phenomena or man-made emergencies including traffic accidents of high severity. FIRST has a module that incorporates analytical approaches to measure street network vulnerability through the calculation of criticality indicators. The module is aimed at measuring the amount of deterioration in the network functionality caused by the partial or total closure of network components within a reference time period.

The approaches combine the structural properties of the street network with traffic demand patterns at different times of day and locations. Each criticality index is estimated by generating a number of shortest paths connecting two nodes extracted according to time dependent OD patterns. Two different types of criticality indicators are estimated: “Centrality” and “Importance”. Centrality indicator depends on the number of Shortest Paths passing through an arc. The effect of removing an arc from the network is considered by the Importance indicator that measures the average increase of travel time produced by the removal of a specific link. Therefore links with high Importance values guarantee an efficient network functionality as its removal causes a significant growth of travel time.

FIRST includes a multi-step preprocessing module to convert raw FCD into a suitable form for detailed traffic and travel analysis. Floating car data are collected by fleets of privately owned vehicles equipped with an on-board unit that stores GPS measurements (position, speed, direction of movement and signal quality).

The preprocessing module is focused on correcting or removing the possible measurement errors caused by failures in the tracking device, reconstructing OD trajectories from sparse sequences of consecutive GPS traces and finally determining the most likely route in the network by matching sequences of positioning data into a street digital map. The map-matching algorithm implemented into the preprocessing module to infer the route traveled by vehicles is really important not only for extracting OD relations between zones and analyzing travel route choice behavior but also for providing travel time data for network performance evaluation and extracting useful traffic patterns such as vehicle turning rates at intersections, origin and destination locations of vehicles moving on a street or congestion levels on network elements, including variations within a day and between weekdays and weekends. Map-matching is also a key process to identify the complex spatial-temporal dependencies between links which are particularly relevant to discover congestion propagation patterns resulting from disruptions.

The occurrence of emergency that disrupts the normal flow of traffic necessitates diversion and routing operations to effectively limit traffic demand approaching the blocked streets. FIRST contains useful modules aimed at supporting the estimation of the impact area around the blocked streets, that will form the search space to find alternative routes, and the identification of upstream intersections potentially affected by queue spillbacks and congestion occurring after disruptions.

FIRST incorporates a module to determine possible diversion routes around the closed streets. This module consists of a two steps approach. The first step involves the OD matrix estimation for the vehicular traffic on the closed links derived from the sample of floating vehicle trajectories crossing the closed streets in the time period of disruption. In the second step the module performs the reassignment of the estimated OD Matrix to the remainder of the network in order to find viable diversion routes, starting and termination points of diversion and critical intersections along each alternative route where changes in traffic signal timing may need to be done to accommodate additional diverted traffic flows.

FIRST processing modules, implemented in Java to ensure platform independence, are accessible through a WebGIS application developed in a complete Open Source environment, including the database PostreSQL and its spatial extension "PostGIS", to facilitate advanced geo-spatial queries and map model results.

The test site of ROME

FIRST modules have been applied and tested to estimate the vulnerability of Rome street network, to examine the effects of traffic disruption and to identify effective traffic diversion strategies. Three different information layers are used: a digital street network database containing topological and functional data of each component, a digital map database of census blocks to design traffic analysis zones and an extended collection of travel data generated by a large fleet of privately-owned vehicles while moving in the study area.

The Tele Atlas MultiNet map database of Rome (Fig. 2) is used in our study as it offers a highly accurate reproduction of the street network including current road attributes, speed restrictions and traffic conditions. The database contains a directed graph with 205.567 nodes and 432.405 arcs.

Each road segment contains several attributes on the functional road class, the direction of traffic flow (one-way, two-way, divided highway), the number of running lanes, the traffic free flow speed, the restricted maneuvers, etc. Among these attributes we pay special attention to "Net2Class" classification because it defines the role that a particular network segment plays in serving traffic flows through the network. Furthermore, there is a relationship between posted speed limits and functional classification.

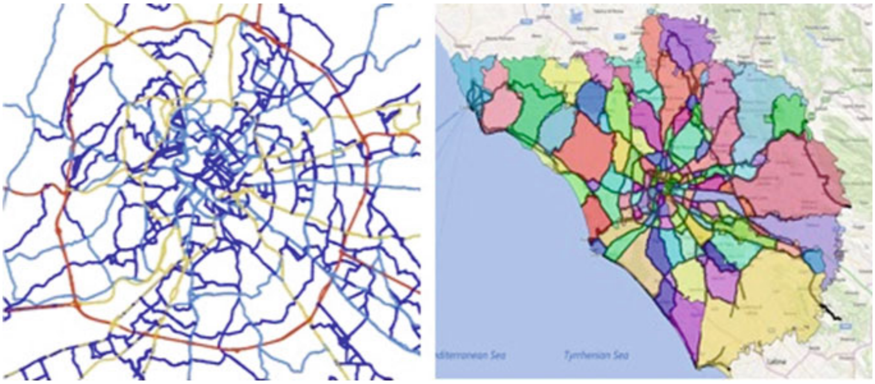

Fig. 2 *Left* Rome MultiNet graph up to Net2Class = 3. *Right* Area zoning outcome

The hierarchical properties of the urban street network are exploited in our approach to restrict the estimation of criticality indexes to major arterial that are designed to provide long-distance movements although shortest path computation is run on the whole street network. After this, we subdivide the study area into 136 Traffic Analysis Zones (TAZs) (Fig. 2) in order to establish the basis from which to estimate Origin-Destination (OD) matrices representing travel demand at a given time window.

A monthly collection of geo-referenced data from an extended fleet of privately owned vehicles traveling within the metropolitan area of Rome has been used. Vehicles are equipped with a tracking device remotely controlled by a software platform operated by OCTOTelematics (http://www.octotelematics.com/en), a company that provides telematics services for insurance companies, car rental and fleet management. From the given collection of about 150×10^6 GPS traces we have extracted approximately 12×10^6 trajectories representing the trips made in Rome by all the equipped vehicles during May 2013.

Vehicle trajectories have been grouped on the basis of the day of the week and six time slots (0–6, 6–9, 9–12, 12–16, 16–20, 20–24) in order to estimate OD matrices for each group. Thus each OD matrix element represents the percentage of trips that flow from a origin TAZ to another destination TAZ in a specific day of the week and a given daily time slot.

Figure 3 shows the criticality maps for the urban street network of Rome. These represent a very useful and intuitive tool for city planners and other decision makers in order to prevent problematic situation and address efforts to solve them.

In Fig. 4, the simulated effects from the temporary closure of a central square (Piazzale Flaminio) and the suggested diversion routes around the closed streets are plotted.

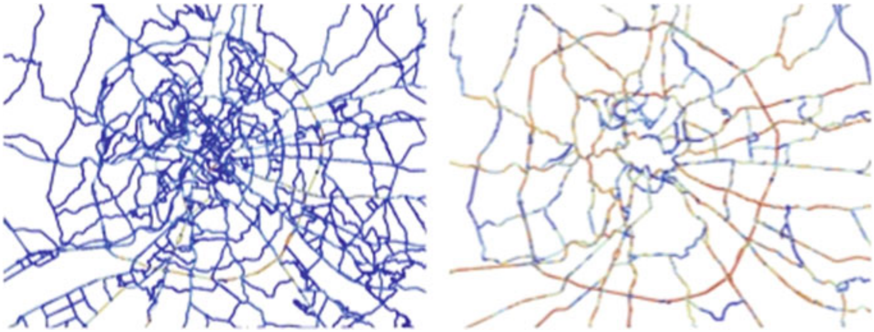

Fig. 3 *Left* Stress Centrality Map over 6 am to 9 am Mondays. *Right* Importance Map over 6 am to 9 am on Mondays

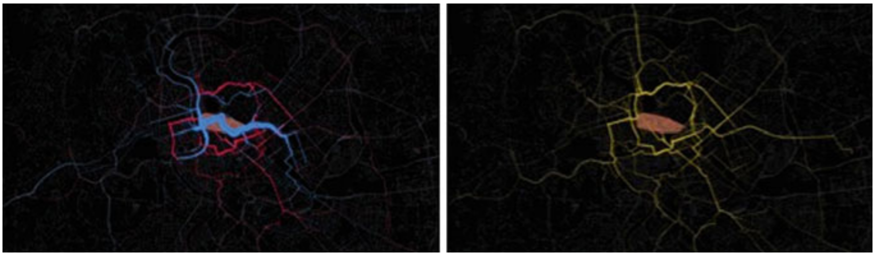

Fig. 4 *Left* Simulated traffic disruptions map. *Right* Diversion routes map

6 Conclusions

In this paper, we provided an extensive description of the modeling and simulation tools used to design and analyze large infrastructures i.e. electric power, telecommunications, water supply and drainage systems, and transportation systems. We showed how simulators can be useful in different phases of the analysis of the behavior of an infrastructure and become an effective means to operators to test several scenarios.

Acknowledgement and Disclaimer This chapter was derived from the FP7 project CIPRNet, which has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 312450.

References

1. Kyriakides E, Polycarpou M (eds) (2015) Intelligent monitoring, control, and security of critical infrastructure systems, studies in computational intelligence. Springer, Berlin
2. Gonzalez-Longatt F, Rueda JL (2014) PowerFactory applications for power system analysis, 1 edn. Springer International Publishing (ISSN: 1612–1287)
3. McCanne S, Floyd S ns–network simulator. http://www-mash.cs.berkeley.edu/ns/
4. Varga A (2001) The OMNeT++ discrete event simulation system. In: Proceedings of the European simulation multiconference (ESM'2001)
5. Liljenstam M, Liu J, Nicol D, Yuan Y, Yan G, Grier C (2005) Rinse: the real-time immersive network simulation environment for network security exercises. In: Workshop on principles of advanced and distributed simulation
6. OPNET (2012) OPNET network simulation tools. http://www.opnet.com (accessed 2013)
7. Tukker M, Kooij CK, Pothof IWM (2013) Hydraulic design and management of wastewater transport systems (CAPWAT Manual), Deltares. ISBN 978-94-91099-12-0. http://capwat.deltares.nl
8. Pothof IWM, Karney B (2012) Guidelines for transient analysis of supply systems. In: Ostfeld A (ed) Water supply system analysis—selected topics, InTech—OpenAccess Publisher, ISBN: 978-953-51-0889-4. http://www.intechopen.com/books/water-supply-system-analysis-selected-topics
9. Zwan S, van der Alidai A, Leruth PH, Pothof IWM (2015) Integration of emergency control systems in the anti-surge design of large transmission schemes. In: Proceedings 12th international conference on pressure surges, 18–20 Nov 2015, Dublin, Ireland, pp 557–565
10. Alidai A, Pothof IWM (2014) Guidelines for hydraulic analysis of treatment plants equipped with ultrafiltration and reverse osmosis membranes. Desalin Water Treat. doi:10.1080/19443994.2014.979244
11. Kooij C, Muhle S, Clemens FHLR, Pothof IWM, Blokzijl FH (2015) Performance indicators for complex wastewater pumping stations and pressure mains. In: 1st international conference on industrial networks and intelligent systems (INISCom), 2–4 March 2015, Tokio, Japan, pp. 94–99
12. van Riel W, van Bueren E, Langeveld J, Herder P, Clemens F (2016) Decision-making for sewer asset management: theory and practice. Urban Water J 13(1):57–68. doi:10.1080/1573062X.2015.1011667
13. Cook DM, Boxall JB (2011) Discoloration material accumulation in water distribution systems. J Pipeline Syst Eng Pract 2(4):113—122
14. Berdica K (2002) An introduction to road vulnerability: what has been done, is done and should be done. Transp Policy 9(2):117–127
15. Mattsson LG, Jenelius E (2015) Vulnerability and resilience of transport systems—a discussion of recent research. Transp Res Part A Policy Pract. Available online 19 June 2015, ISSN 0965-8564, http://dx.doi.org/10.1016/j.tra.2015.06.002
16. Murray AT, Grubesic TH (2007) Critical infrastructures, reliability and vulnerability. Springer, Berlin
17. Jenelius E, Petersen T, Mattsson L-G (2006) Importance and exposure in road network vulnerability analysis. Transp Res Part A 40(7):537–560
18. Demšar U, Špatenková O, Virrantaus K (2008) Identifying critical locations in a spatial network with graph theory. Trans GIS 12(1):61–82
19. Jiang B, Claramunt C (2004) Topological analysis of urban street networks. Environ Plan 31:151–162
20. Newmann M (2010) Networks: an introduction. Oxford University Press, Inc., New York, NY, USA
21. Porta S, Crucitti P, Latora V (2006) The network analysis of urban streets: a primal approach. Environ Plan 33:705–725

22. Strano E et al (2013) Urban street networks, a comparative analysis of ten European cities. Environ Plan 40(6):1071–1086
23. Nicholson A, Du Z-P (1997) Degradable transportation systems: an integrated equilibrium model. Transp Res Part B 31(3):209–223