# Chapter 1
# Introduction

**Kyriazis Pitilakis and Paolo Franchin**

**Abstract** This chapter outlines the SYNER-G project, its objectives and structure. A short literature review of the vulnerability and risk assessment of infrastructural systems and their components highlights the framework of the past works and the challenges anticipated. The main issues for the systemic risk analysis are shortly described including the SYNER-G taxonomy, the seismic hazard estimates, the intensity measures and fragility curves, the systemic analysis methods and performance indicators, the treatment of uncertainties and socio-economic issues of the analysis. Finally, the applications that have been performed to test the SYNER-G methodology and tools are also outlined.

## 1.1 Background: Scope and Aim of the Book

The book presents the results of the work carried out within the SYNER-G project (see Sect. 1.3) on the physical modelling of the systems made up of several components, of their interactions, of the seismic hazard acting upon them and of all the relevant uncertainties that affect the evaluation of the systemic vulnerability. The book is closely related to a previous one in the same series of Springer editions, entitled *"SYNER-G: Typology definition and fragility functions for physical elements at seismic risk"* (Pitilakis et al. 2014). The later is devoted to the characterization of components' fragility.

K. Pitilakis (✉)
Department of Civil Engineering, Aristotle University, 54124 Thessaloniki, Greece
e-mail: kpitilak@civil.auth.gr

P. Franchin
Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Via Gramsci 53, 00197 Rome, Italy
e-mail: paolo.franchin@uniroma1.it

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The present book is comprised of two parts: Part I collects Chaps. 2, 3, 4, and 5 and presents models and methods for systemic analysis, while Part II (Chaps. 6, 7, 8, 9, 10, 11, and 12) illustrates their application to a number of case studies employed during the project as test beds.

Chapter 2 focuses on the methodological framework developed to bind together all the necessary models and describes the probabilistic assessment procedure used to evaluate performance indicators.

Chapter 3 discusses the distributed seismic hazard model employed to predict probabilistically and physically consistent vector fields of intensity ("shake fields"), to be fed to all components in order to evaluate their state of physical damage.

Chapter 4 introduces the methodological advancements made in the modelling of the social consequences/impact of the earthquake within the framework of multi-criteria decision analysis.

Chapter 5, finally, describes the specification of the general methodology (Chap. 2) to all the systems considered in the detailed taxonomy drawn within SYNER-G, and reported later in Sect. 1.4.

The chapters in Part II illustrate the applications of the SYNER-G methodology and tools for the analysis to selected systems, as a gas distribution network, a road network, an electric power network, a regional health care system, a district in Vienna, the city of Thessaloniki and the harbour of the latter.

## 1.2 Literature Review

The degree to which our society depends upon the reliable functioning of infrastructural systems and more in general of the built environment is underlined by the ubiquitous term *critical infrastructures* (CI) with which this set of interconnected systems is indicated (PCCIP 1997).

This extreme dependence and the increased vulnerability of CI, due to ageing but also and more importantly to the ever deeper interdependence, are somewhat ironically paralleled by very high expectations on their performance held by the general public: CI tends to be given for granted most of the time, until of course spectacular and unexpected failures occur (Macaulay 2008). These failures, however, are not unexpected at all to emergency managers and researchers in the field.

The literature on vulnerability of infrastructural systems and their components to natural disasters as well as to targeted malevolent actions is vast. It must be recognized, however, that the largest proportion of these studies focuses on single systems, without considering interactions, cascading failures, and complex impacts. These studies, which in some cases started very early, have covered[1] buildings

[1] The references cited in this section by no means intend to be an exhaustive review of the relevant literature, and they represent only a subjective selection for illustrative purposes.

(Rossetto and Elnashai 2003; Spence et al. 2007; Goda and Hong 2008; Bal et al. 2010; Parodi et al. 2010) but also utilities, with a fairly large number of contributions on water supply networks (Isoyama and Katayama 1981; Shinozuka et al. 1981, 1992; O'Rourke et al. 1985; Ballantyne et al. 1990; Kawakami 1990; Taylor 1991; Awumah et al. 1991; ATC-25 1992; Markov et al. 1994; Hwang et al. 1998; Chang et al. 2002; Hoshiya and Yamamoto 2002; Kalungi and Tanyimboh 2003; Hoshiya et al. 2004; Adachi and Ellingwood 2006; Scawthorn et al. 2006; Javanbarg et al. 2006; Li et al. 2006; Shi et al. 2006; Javanbarg and Takada 2009; Wang et al. 2010), on electric power grids (Matsuda et al. 1991; Pires et al. 1996; Vanzi 1996, 2000; Giannini et al. 1999; Xingbin and Singh 2004; Helseth and Holen 2006; Shumuta 2007; Nuti et al. 2007; Schläpfer et al. 2008; Arianos et al. 2009; Ma et al. 2010; Bompard et al. 2011; Buritica et al. 2012), a relatively minor number of works on gas distribution networks (O'Rourke and Palmer 1996; Helseth and Holen 2006; Chang and Song 2007; Kim and Kang 2013). Transportation systems have also been the object of several studies (Shinozuka et al. 2003a, b; Zhou et al. 2004; Franchin et al. 2006; Shiraki et al. 2007; Kiremidjian et al. 2007; Kang et al. 2008; Chang et al. 2011).

The importance of the interconnection between different systems is a more recent acquisition (PCCIP 1997; Kameda 2000; Rinaldi et al. 2001; Peerenboom et al. 2001; Little 2002; Menoni et al. 2002; Li and He (2002), Bush et al. 2003; Benoît et al. 2003; Yao et al. 2004; Rinaldi 2004; Karaca 2005; Dudenhoeffer and Permann 2006; Leung et al. 2007; Laprie et al. 2007; Cardellini et al. 2007; Dueñas-Osorio et al. 2007a, b; Tang and Wen 2008; Rosato et al. 2008; Adachi and Ellingwood 2008; Dueñas-Osorio and Vemuru 2009; Ouyang et al. 2009; Shizuma et al. 2009; Nojima 2010; Johansson and Hassel 2010; Zhang and Peeta 2011; Hernandez-Fajardo and Dueñas-Osorio 2011; Dueñas-Osorio and Kwasinski 2012) and studies that target two or, rarely, more systems are relatively few (Kim et al. 2007; Cagno et al. 2011; Ouyang and Dueñas-Osorio 2011; Poljanšek et al. 2012; Hernandez-Fajardo and Dueñas-Osorio 2013).

In parallel with the above studies some large concerted efforts to come up with frameworks and tools for carrying out vulnerability and loss assessment at the regional or urban scale, have been funded in the US. These are the HAZUS (FEMA 1999) and the MAEviz (MAE 2013) initiatives. Other initiatives aimed at developing tools for regional risk/loss estimation include e.g. Rt (Mahsuli and Haukaas 2013) and CAPRA (Cardona et al. 2012). Finally, the most ambitious current project to develop a globally applicable consistent and extensible regional loss estimation methodology is the Global Earthquake Model (GEM 2013).

The National Institute for Building Sciences (NIBS) originally developed HAZUS (Hazard U.S.) on behalf of the Federal Emergency Management Agency (FEMA) back in the 1990 as a closed system, limited to seismic hazard and to U.S.A. scenarios. The current version, called HAZUS-MH (MR4) includes multiple hazards (earthquakes, hurricanes and floods), up to date inventory data and hazard characterization, and efforts have been made to develop an internationally applicable version, which has results so far in HAZ-TAIWAN, a country-specific release for Taiwan (Yeh et al. 2006). The main merit of the HAZUS platform is that of having provided for the first time an unparalleled set of fragility models for basically every component in every system in which the built environment can be subdivided. It must be recognized, however, that many of these models have been derived based solely on expert judgment and overall the consistency of derivation is limited. One effect of the sheer size of the HAZUS framework and set of tools is that it established itself very soon as the reference for all studies in the sector. By so doing, some of the basic choices made during its development have had a very important influence in the following research. For instance, many researchers have adopted as a default choice, somewhat uncritically, the five damage states/levels introduced by HAZUS. Most fragility studies published after its appearance employed this discretization of damage that, in many cases, can be too refined for the considered component. Also, HAZUS has basically introduced the lognormal distribution for fragility functions, rapidly become the de facto standard.

The development of MAEviz (later re-branded as the Earthquake module of Multi-Hazard Assessment, Response, and Planning, mHARP-EQ, and recently renamed ERGO-EQ) started somewhat later than HAZUS and was the product of the research efforts carried out at the Mid-America Earthquake Centre in collaboration with the National Center for Supercomputing Applications' (NCSA). In particular, MAEviz is an open-source and incorporates many of the design concepts and capabilities motivated by NCSA efforts to develop "Cyberenvironments" that span scientific disciplines and that can rapidly evolve to incorporate new research results (Elnashai et al. 2008). An important aspect of MAEviz is its extensibility, both in terms of analysis/features modules, and of visualization/representation (GIS) modules. The framework has been designed to implement the Consequence-based Risk Management (CRM) paradigm supported by the MAE center.

A different view characterizes the software 'Rt', the outcome of continuous development started with 'InRisk', a the 3 years research project on Infrastructure Risk funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) started in 2006. Rt is a computer program for reliability and optimization analysis with multiple probabilistic models. To orchestrate the multi-model analyses, Rt has an object-oriented architecture. Rt is also fully parameterized, with individual objects for random variables, design variables, and model responses. The main emphasis of the project and of the developed software is on the adoption of proper probabilistic models, i.e. models that provide a deterministic output when fed with a deterministic input. In this respect, Rt is probably a unicum in the current landscape of framework for infrastructure risk assessment, in that it does not make use of almost ubiquitous fragility functions.

The Central American Probabilistic Risk Assessment (CAPRA) platform was developed in partnership with Central American governments, the support of the Central American Coordination Centre for Disaster Prevention (CEPREDENAC), the Inter-American Development Bank (IDB) and the International Strategy of United Nations for Disaster Reduction (UN-ISDR) and the World Bank. It is a free, modular, extensible platform aimed at risk analysis and decision making. Modularity means that hazard information is combined with exposure and physical vulnerability data, allowing the user to determine conjoint or cascade risk on an inter-related multi-hazard basis, distinguishing the platform from previous single hazard analyses. The CAPRA suite of software includes hazard mapping, risk assessment and cost-benefit analysis tools to support pro-active risk management. CAPRA can also be used to design risk-financing strategies.

The GEM initiative aims to build state-of-the-art, widely accepted basic datasets, models, best-practice and software/tools for the assessment of seismic risk on a global scale (Crowley et al. 2013). The ambitious project has started in response to the fact that while vulnerability to earthquakes is increasing, reliable risk assessment tools and data are most often still out of reach in many areas of the world. The non-profit and independent GEM Foundation drives the effort, and receives funding and support from both the public and private sector.

## 1.3 The SYNER-G Project: Short Description

SYNER-G is a collaborative integrated research project funded (2009–2013) by the European Commission Directorate-General for Research within the so-called Framework Programme 7. The 14 Consortium partners include representative institutions from many European countries, as well as non-funded international partners and industry representatives, as shown in Fig. 1.1.

The project proposal started from acknowledging that: (a) previous research on the seismic risk and vulnerability assessment of urban systems (buildings, building aggregates, lifeline networks and critical infrastructures), at international, European and national levels, were focused on the vulnerability of individual elements at risk, and there was a need for constraining the uncertainty associated with the employed

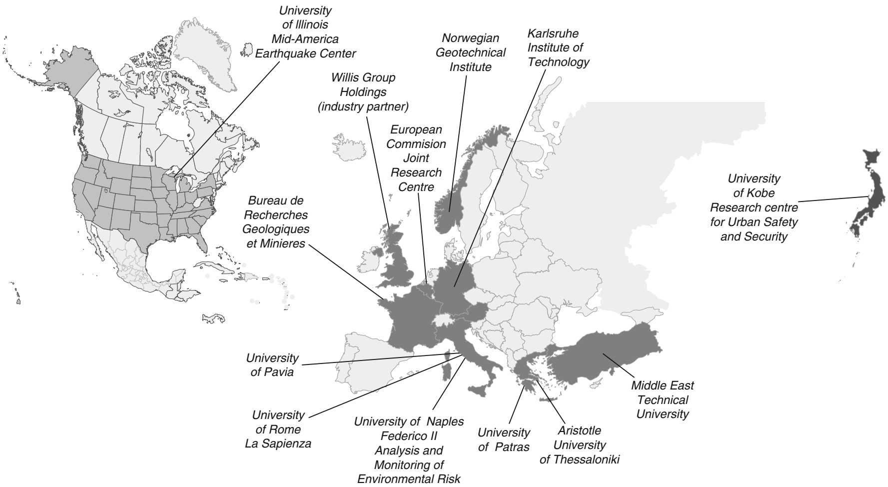


Fig. 1.1 Partners in the SYNER-G consortium

fragility and loss models; (b) most fragility models were developed outside Europe and their applicability for elements at risk in the European context was to be assessed; (c) systemic vulnerability and the associated increased impact had not been considered so far in a rigorous and unified way for all kind of systems; (d) the ability to model damage to non-structural systems and social and economic consequences was in need of significant improvement.

Therefore the project goal was to revise and when necessary propose fragility models to be applied in the European context, and to develop a systemic and holistic approach to loss estimation able to capture final loss estimates at the global level (i.e. socio-economic impacts), accounting for their dependence on the vulnerability and interactions of the whole system.

The work was organized into packages (WPs) as shown in Fig. 1.2, with the core technical WPs being numbered 2–6. One of the first tasks to be completed within WP2, and one that was instrumental to set all other WPs in motion, was the definition and preliminary description of the domain to be studied. This resulted in a detailed taxonomy of the system of systems that makes up the "Infrastructure", which is briefly outlined in Sect. 1.4. Work then started in parallel on the components' and the systemic lines, with WP3 focusing on the collection, review and proposal of fragility models for all elements in the taxonomy, and WP2 aimed at developing a framework for systemic analysis in close interaction with WP4 (socio-economic impacts) and WP5 (specification of the general methodology to each system in the taxonomy).

Shortly after the initial phase, data collection on the case studies in WP6 was started, especially for the two main applications to the cities of Thessaloniki and Vienna. The unfortunate occurrence of the April 6th 2009 earthquake in L'Aquila after the project submission provided another important case study, the gas network of L'Aquila that was included in the work programme after the project kick-off.

## 1.4 Elements at Risk and Taxonomy

The first task undertaken within the project was the identification and description of a set of systems, sub-systems and components to focus on. This has resulted in what is called the SYNER-G taxonomy, described in this section. A more detailed version of this taxonomy can be found in the SYNER-G reference report 2 (Hancilar and Taucer 2013). All considered systems and their components have been assigned unique tags used consistently throughout the project. This taxonomy has been the guidance for the work carried out within work packages 3 (physical vulnerability and losses) and 5 (socio-economic vulnerability and losses), where typology fragility models have been revised and/or developed for each component, with a focus on European distinctive features, and systems have been modelled, respectively (Fig. 1.3).

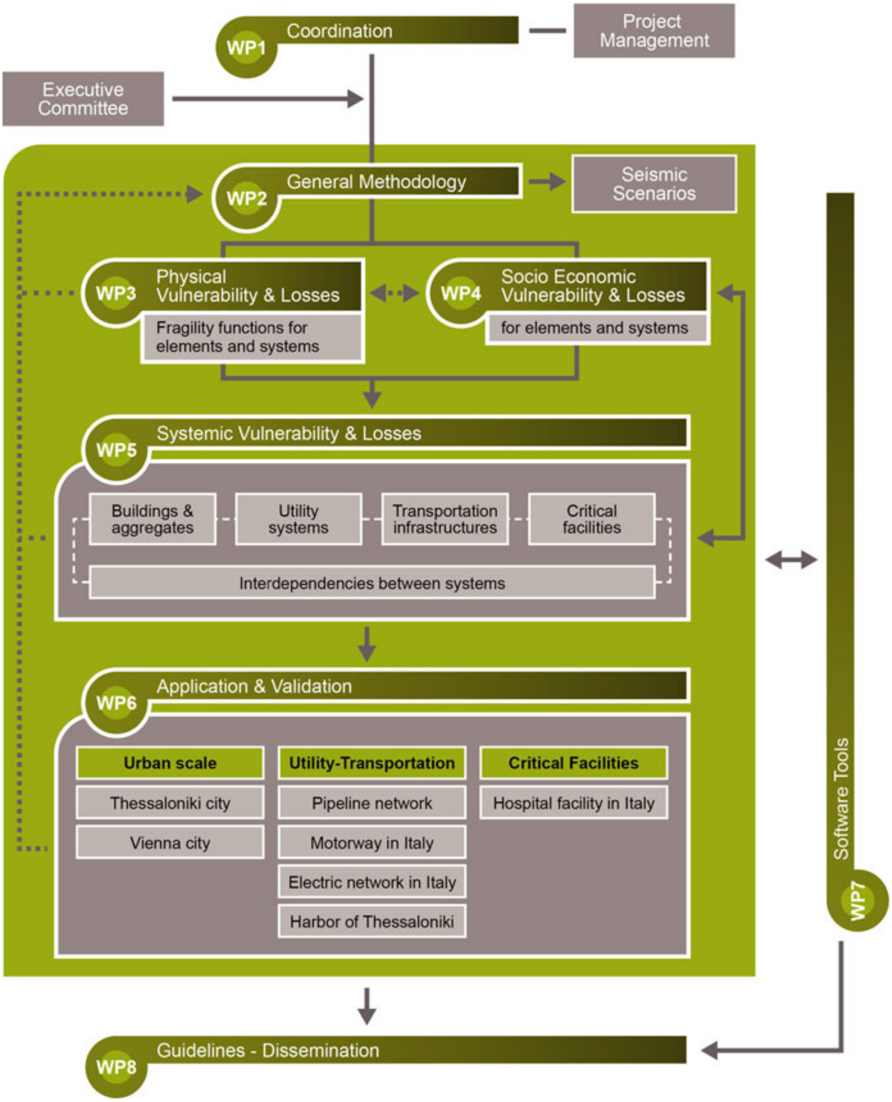


**Fig. 1.2** The project workflow and subdivision into work-packages

### *1.4.1 Building Aggregates (BDG)*

Buildings are the basic point-like component of building aggregates/agglomerates/ blocks (where buildings may or may not be in contact, with the ensuing interactions), which are delimited by roads and served by all other utility systems.

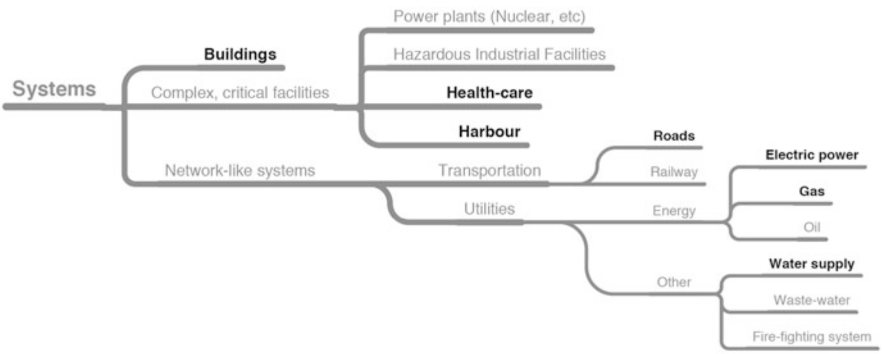


**Fig. 1.3** Systems considered in the SYNER-G taxonomy: systems that have been developed and implemented in the model are in *bold black* typeface

The description of the vulnerability of an urbanized area (e.g. a census tract, where several such building agglomerates are present) for the purpose of a system study requires fragility analysis of representative buildings for each typology, and statistical data on the incidence of each typology in the building population and services. Buildings are mainly described and classified by the following parameters: Force Resisting Mechanism (FRM1), FRM Material (FRMM1), Plan (P), Elevation (E), Cladding (C), Detailing (D), Floor System (FS), Roof System (RS), Height Level (HL), Code Level (CL).

## *1.4.2 Electric Power Network (EPN)*

The electric-power system as a whole is composed of a number of point-like critical facilities (i.e. power generation facilities, transformation substations) and of the electric power transmission network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system can be subdivided into four major parts: Generation, Transformation, Transmission and Distribution and Loads.

The identified main system components are:

- EPN01: Electric power grid
- EPN02: Generation plant
- EPN03: Substation (distribution, transformation-distribution)
- EPN04: Distribution circuits
- EPN05-09: Substation macro-components
- EPN10-23: Substation micro-components
- EPN24: Transmission or distribution line

### 1.4.3 Natural Gas System (GAS) and Oil System (OIL)

The natural gas or oil system as a whole is composed of a number of point-like critical facilities (i.e. production and gathering facilities, treatment plants, storage facilities, intermediate stations where gas is pressurized/depressurized or simply metered) and of the transmission/distribution network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system is made of pipelines and of the supervisory control and data acquisition (SCADA) sub-system.

The identified components for GAS system are:

- GAS01: Production and gathering facility (Onshore, Offshore)
- GAS02: Treatment plant
- GAS03: Storage tank farm
- GAS04: Station (Compression, Metering Compression/metering, Regulator/metering)
- GAS05: Pipe
- GAS06: SCADA

The identified components for OIL system are:

- OIL01: Production and gathering facility (onshore, offshore)
- OIL02: Refinery
- OIL03: Storage tank farm
- OIL04: Pumping plant
- OIL05: Pipe
- OIL06: SCADA

### 1.4.4 Water Supply System (WSS)

The water-supply system as a whole is composed of a number of point-like critical facilities (i.e. water sources, treatment plants, pumping stations, storage tanks) and the water distribution network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system is made of pipelines, tunnels and canals and the supervisory control and data acquisition – SCADA – sub-system.

The identified system components are:

- WSS01: Source (springs, rivers, natural lakes, impounding reservoirs, shallow or deep wells)
- WSS02: Treatment plant
- WSS03: Pumping station
- WSS04: Storage tank
- WSS05: Pipe

- WSS06: Tunnel
- WSS07: Canal
- WSS08: SCADA system

### *1.4.5 Waste Water Network (WWN)*

The waste water system as a whole is composed of a number of point-like critical facilities (i.e. treatment plants, pumping stations) and of the distribution network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system is made of pipelines, tunnels.

The identified system components are:

- WWN01: Waste-water treatment plant
- WWN02: Pumping (lift) station
- WWN03: Pipe
- WWN04: Tunnel
- WWN05: SCADA system

### *1.4.6 Road Network (RDN)*

The road network is composed of a number of nodes and edges. It is a transportation network where edges can be directed (one-way) or undirected (two-way). All edges are in general vulnerable to seismic shaking or geotechnical hazards, with pavements that can rupture due to surface ground deformation. Some types of edges or road segments, like those identified below have specific types of response to seismic action and associated vulnerability.

The main identified system components are:

- RDN01: Bridge
- RDN02: Tunnel
- RDN03: Embankment (road on)
- RDN04: Trench (road in)
- RDN05: Unstable slope (road on, or running along)
- RDN06: Road pavement (ground failure)
- RDN07: Bridge abutment

### *1.4.7 Railway Network (RWN)*

The railway system as a whole is composed of a number of point-like critical facilities (stations) and of the railway network itself. The internal logic of the stations and their function in the traffic management of the whole system should be modelled explicitly. The network portion of the system has the same components as a road network, plus a supervisory control and data acquisition – SCADA – sub-system. The difference is in the fragility models: the underlying limit-state relative to continued traffic over railway bridges, embankments, etc. must consider the limitation and tolerances associated with the tracks. This will lead in general to limitations to relative, maximum and residual, displacements stricter than for roadway bridges.

The identified system components are:

- RWN01: Bridge
- RWN02: Tunnel
- RWN03: Embankment (track on)
- RWN04: Trench (track in a)
- RWN05: Unstable slope (track on, or running along)
- RWN06: Track
- RWN07: Bridge abutment
- RWN08: Station

### *1.4.8 Harbour (HBR)*

A harbour is a complex system comprising all the activities related to the transfer of goods/passengers between the maritime transportation and the earth-bound transportation systems. It is serviced by a number of other systems including: EPN, WSN, WWN, FFS, GAS, RDN, RWN. The identified system components are:

- HBR01: Waterfront components (wharves, breakwaters, etc.)
- HBR02: Earthen embankments (hydraulic fills and native soil material)
- HBR03: Cargo handling and storage components (cranes, tanks, etc.)
- HBR04: Buildings (sheds, warehouse, offices, etc.)
- HBR05: Liquid fuel system (components as per the OIL system)
- Utility systems and transportation networks

### *1.4.9 Health-Care System (HCS)*

The health-care system is made up of health-care facilities (HCF), or hospitals. Hospitals are systems whose function is to deliver medical services. From a social point of view, hospitals provide a fundamental assistance to citizens in every-day life; their function becomes of paramount importance in the case of an earthquake event. This is the reason for including them among the critical facilities group.

Medical services, which consist of standardized procedures to guarantee an adequate treatment of patients, are delivered to patients by a joint contribution of the three "active" components of the system:

- The *operators* (human component): doctors, nurses and in general whoever plays an active role in providing medical care;
- The *facility* (physical component): where medical services are delivered;
- The *organisation* (organizational component): hospital management, responsible of setting up adequate conditions (standardized procedures for ordinary and emergency conditions) so that the medical services can be delivered.

The identified system components are:

- HCS01: Organisational component
- HCS02: Human component
- HCS03: Physical component
  - HCS03-1: Structural elements (of the buildings within the complex/facility)
  - HCS03-2: Non-structural elements
  - HCS03-3: Architectural (walls, ceilings, windows etc.)
  - HCS03-4: Basic installations (generation/distribution)
  - HCS03-5: Basic installations/medical gases
  - HCS03-6: Basic installations/power system
  - HCS03-7: Basic installations/water system
  - HCS03-8: Basic installations/conveying system
  - HCS03-9: Building contents

### *1.4.10 Fire-Fighting System (FFS)*

The fire-fighting system as a whole can be a separate system or part of the WSS. In case it is a separate system, it is composed of a number of point-like facilities (i.e. fire-fighters stations, pumping stations, storage tanks, fire-hydrant) and of the distribution network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system is made of pipelines.

The identified system components are:

- FFS01: Fire-fighters station
- FFS02: Pumping station
- FFS03: Storage tank
- FFS04: Fire-hydrant
- FFS05: Pipe

## 1.5 Important Issues in the Systemic Seismic Risk Analysis

### *1.5.1 Seismic Hazard Assessment*

The seismic hazard assessment of spatially distributed systems with various typologies differs from the point like hazard assessment. In Chap. 3 an innovative comprehensive approach is presented, summarized herein by making reference to the abstract of the relevant Chapter. "*The analysis of seismic risk to multiple systems of spatially distributed infrastructures presents new challenges in the characterisation of the seismic hazard input. A general procedure entitled "Shakefield" is established within SYNER-G, which allows for the generation of samples of ground motion fields for both single scenario events, and for stochastically generated sets of events needed for probabilistic seismic risk analysis. For a spatially distributed infrastructure of vulnerable elements, the spatial correlation of the ground motion fields for different measures of the ground motion intensity is incorporated into the simulation procedure. This is extended further to consider spatial cross-correlation between different measures of ground motion intensity. In addition to the characterisation of the seismic hazard from transient ground motion, the simulation procedure is extended to consider secondary geotechnical effects from earthquake shaking. Thus the Shakefield procedure can also characterise the site effects, site amplification and transient strain, and also provide estimates of permanent ground displacement due to liquefaction, slope displacement and coseismic fault rupture*".

### *1.5.2 Intensity Measures*

A main issue related to the fragility curves is the selection of an appropriate earthquake Intensity Measure (IM) for each Infrastructure class and component that characterizes the strong ground motion and best correlates with the response of each element, for example, building, pipeline or harbour facilities like cranes. Examples of IMs include the peak ground acceleration/velocity/displacement or the spectral acceleration/velocity/displacement. Each intensity measure may describe different characteristics of the motion, some of which may be more adverse for the structure or system under consideration. SYNER-G encompasses an extensive review of common IMs for each element at risk.

### *1.5.3 Fragility Curves*

Fragility curves constitute one of the key elements of seismic risk assessment. They relate the seismic intensity to the probability of reaching or exceeding a level of damage (e.g. minor, moderate, extensive, collapse) for the elements at risk. Several methods are available in the literature to derive fragility functions for different elements exposed to seismic and geotechnical hazard. Conventionally, they are classified into four categories: empirical, expert elicitation, analytical and hybrid. In the framework of SYNER-G a comprehensive review of fragility functions for most important elements at risk has been carried out. Moreover, new fragility curves have been developed where necessary, considering the distinctive features of European elements. The result of these studies is presented in a joint volume also published in Springer (Pitilakis et al. 2014).

### *1.5.4 Systemic Analysis and Performance Indicators*

The quantitative measure of the performance of the whole system and its elements when subjected to a seismic hazard is given by Performance Indicators (PI's). They express numerically either the comparison of a demand with a capacity quantity, or the consequence of a mitigation action, or the assembled consequences of all damages (the "impact"). Performance indicators, at the component or the system level, depend on the type of analysis that is performed. Four main types of system evaluations are considered in the SYNER-G approach (Chap. 5):

- **Vulnerability analysis:** This level considers only the potential physical damages of the components of the systems, with no consideration of functionality of either the elements or the whole system.
- **Connectivity analysis:** Here the probability of the demand nodes to be connected to functioning supply nodes through undamaged paths is analyzed. In this approach the damaged components are removed from the network and the adjacency matrix is updated accordingly, thus pointing out the nodes or areas that are disconnected from the rest of the system. This qualitative approach is used for all utility networks (water, electricity, gas) and the road transportation system. Connectivity analysis gives access to indices such as the connectivity loss (measure of the reduction of the number of possible paths from sources to sinks).
- **Capacity analysis**: The ability of the system to provide to the users the required functionality is quantified. For utility networks, graph algorithms and flow equations can be used to estimate capacitive flows from sources (e.g. generators, reservoirs) to sinks (i.e. distribution nodes), based on the damages sustained by the network components (from total destruction to slight damages reducing the capacity). Capacitive modelling yields more elaborate performance indicators at the distribution nodes (e.g. head ratio for water system, voltage ratio for electric buses) or for the whole system (e.g. system serviceability index comparing the customer demand satisfaction before and after the seismic event).
- **Fault-tree analysis**: It concerns critical infrastructures, where multiple conditions are necessary for the systems to ensure its function. This approach aims to

evaluate the remaining operating capacity of objects such as health-care facilities. The system is broken down into structural, non-structural or human components, each one of them being connected with logic operators. It is generally used for the derivation of fragility curves for specific components that comprise a set of sub-components (e.g. health care facilities, water treatment plants).

### *1.5.5 Treatment of Uncertainties*

Several sources of uncertainties are inherent in the analysis, which are related among others to the seismic hazard and spatial correlation models, the fragility and loss assessment or the functionality thresholds of each component, the methods to estimate adequate fragility curves, and the data available for the different infrastructures and systems. The SYNER-G methodology incorporates a rather comprehensive representation of uncertainty in the problem, with a refined and effective seismic hazard model (Chap. 3) and vulnerability model (Chap. 5), including epistemic modelling of the uncertainty in a hierarchical fashion.

### *1.5.6 Socioeconomic Analysis*

An important issue in the seismic risk analysis of urban systems is to compute the expected social losses such as displaced population, shelter needs or health impacts. Economic losses are by themselves another important issue which is not treated explicitly in this volume. This way of conceptualizing integrated risk emphasizes the importance of understanding the interrelations between physical and social systems. In other words, the goal of the present effort is to provide a methodology and a tool on how direct physical losses can potentially aggravate existing vulnerabilities in society and how these vulnerabilities can ultimately lead to greater impacts from physical damage and losses.

A unified approach for modelling shelter needs and health impacts caused by earthquake damage has been developed in SYNER-G. In particular, the proposed models bring together the state-of-the-art casualty and displaced population estimation models into a comprehensive modelling approach based on multi-criteria decision support, which provides decision makers with a dynamic platform to capture post-disaster emergency shelter demand and health impact decisions. The focus in the shelter needs model is to obtain shelter demand as a consequence of building usability, building habitability and social vulnerability of the affected population rather than building damage alone. The shelter model simulates households' decision-making and considers physical, socio-economic, climatic, spatial and temporal factors in addition to modelled building damage states. The health impact model combines a new semi-empirical methodology for casualty estimation with models of health impact vulnerability, and transportation accessibility to obtain a holistic assessment of health impacts in the emergency period after earthquakes.

The models for shelter needs proposed in the present state of SYNER-G could be expanded to cover other post-earthquake needs in the frame of seismic risk management, mitigation and preparedness.

## 1.6 Applications

The applicability of the SYNER-G methodology and tools is tested through several case studies at urban and regional level as well as at complex infrastructure level. In particular, the following case studies are presented in Part II:

The **city of Thessaloniki** in Northern Greece (Chap. 7). The study area covers the municipality of Thessaloniki, which is divided in 20 Sub City Districts. It includes the building stock (BDG), road network (RDN), water supply system (WSS) and electric power network (EPN), considering specific interdependencies between systems. The purpose of this application is to study the systemic risk in a large urban area of high seismicity and to investigate the effect of interactions between systems in terms of network connectivity loss or displaced people. Furthermore, an accessibility analysis to hospital facilities considering the damages in RDN is performed (Chap. 4) and a shelter demand analysis based on a multi-criteria approach is applied (Chap. 7). Through the latter application, the districts with higher needs for shelters are identified, supporting in this way an efficient planning of shelter allocation.

The **Brigittenau district in Vienna**, Austria (Chap. 8). It is a heavily populated urban area with many residential buildings and several networks and infrastructures exposed to relatively low seismic risk. This test case is mainly an attempt to look at SYNER-G methods at the building level, using high-resolution data in a small area.

The medium-pressure **gas distribution system of L'Aquila** in Italy (Chap. 9). The functionality of the network is examined through a connectivity analysis considering the pipelines and the Reduction Groups (M/R stations). A probabilistic seismic and geotechnical (landslide) hazard analysis is performed based on characteristic earthquakes of moment magnitude $M_w = 6.3$, generated by the Paganica fault.

The **road network of Calabria region** in Southern Italy (Chap. 10). A pure connectivity analysis is performed and specific performance indicators that describe the loss of connectivity between traffic analysis zones and minimum travel time to reach a hospital are applied. The seismic hazard is modeled through 20 faults of the broader area.

The **electric power network of Sicily** in Italy (Chap. 10). The study here is carried out at the capacitive level, i.e. computing the actual power flows, voltages and currents in the network, both in the undamaged or reference state and in the damaged one. The seismic hazard is modeled through 18 faults of the broader area.

A **regional health care system** (Chap. 11). The earthquake effects both on hospitals and on the RDN, connecting towns to hospitals, are evaluated and the interaction among them is accounted. The estimated risk is described through several indicators such as the un-hospitalized victims, the inability of hospitals to provide medical care, the demand of medical care on hospitals or the hospitalization travel time.

The **harbour of Thessaloniki** in Greece (Chap. 12). The performance of the harbour is measured with the total cargo/containers handled and/or delivered (to the port's gate) in a pre-defined time frame per terminal and for the whole port system, considering the seismic damages as well as specific interdependencies. In particular, the effect of disruption of electric power supply to cranes and road closures due to building collapses is analyzed.

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