Systemic seismic vulnerability and loss assessment: Validation studies

SYNER-G Reference Report 6

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Foreword

SYNER-G is a European collaborative research project funded by European Commission (Seventh Framework Program, Theme 6: Environment) under Grant Agreement no. 244061. The primary purpose of SYNER-G is to develop an integrated methodology for the systemic seismic vulnerability and risk analysis of buildings, transportation and utility networks and critical facilities, considering for the interactions between different components and systems. The whole methodology is implemented in an open source software tool and is validated in selected case studies. The research consortium relies on the active participation of twelve entities from Europe, one from USA and one from Japan. The consortium includes partners from the consulting and the insurance industry.

SYNER-G developed an innovative methodological framework for the assessment of physical as well as socio-economic seismic vulnerability and risk at the urban/regional level. The built environment is modelled according to a detailed taxonomy, grouped into the following categories: buildings, transportation and utility networks, and critical facilities. Each category may have several types of components and systems. The framework encompasses in an integrated fashion all aspects in the chain, from hazard to the vulnerability assessment of components and systems and to the socio-economic impacts of an earthquake, accounting for all relevant uncertainties within an efficient quantitative simulation scheme, and modelling interactions between the multiple component systems.

The methodology and software tools are validated in selected sites and systems in urban and regional scale: city of Thessaloniki (Greece), city of Vienna (Austria), harbour of Thessaloniki, gas system of L’Aquila in Italy, electric power network, roadway network and hospital facility again in Italy.

The scope of the present series of Reference Reports is to document the methods, procedures, tools and applications that have been developed in SYNER-G. The reports are intended to researchers, professionals, stakeholders as well as representatives from civil protection, insurance and industry areas involved in seismic risk assessment and management.

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Abstract

The SYNER-G project aims at developing a methodology to evaluate the seismic vulnerability to earthquakes of a complex system of interconnected infrastructural systems of regional/urban extension. This report summarizes the application of the SYNER-G methodology and tools to selected case studies of regional and urban extension: the city of Thessaloniki; the city of Vienna; the gas system of L’Aquila in Italy; the road network of Calabria region in Southern Italy; the electric power network of Sicily; a hospital facility in Italy; the harbor of Thessaloniki. For each case study the following items are given: general description of the test site, seismic hazard issues, systemic vulnerability methodology, software developments and implementation, system topology and characteristics, description of the input, results of the application. Through these studies the different steps of the SYNER-G methodology are validated and demonstrated.

Keywords: Thessaloniki city, Vienna city, L’Aquila city, Sicily, South Italy, gas system, water supply system, road network, electric power network, hospital facility, harbor, fragility, vulnerability, systemic analysis, losses, risk assessment
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1 Introduction and objectives

1.1 CONTENT AND OBJECTIVES OF THE REPORT

This reference report presents the application and test of applicability of the SYNER-G methodology and software tools in selected case studies at urban level (city of Thessaloniki in Greece, city of Vienna in Austria) and regional level (gas network of L’Aquila in Italy, transportation network in South Italy, electric power network in Sicily) as well as in complex infrastructures (hospital facility in Italy, harbor of Thessaloniki) accounting for inter- and intra-dependencies among infrastructural components.

The object-oriented paradigm (OOP) has been adopted for the purpose of modeling the infrastructure and the seismic hazard. Within the OOP, the problem is described as a set of objects, characterized in terms of attributes (or properties) and methods, that interact with each other. Objects are instances (concrete realizations) of classes (abstract models, or templates for all objects with the same set of properties and methods). The SYNER-G prototype software includes an object-oriented representation of a subset of all the systems in the taxonomy.

Each case study comprises a separate chapter of the report including the following items: general description of the test site, seismic hazard issues, systemic vulnerability methodology, software developments and implementation, system topology and characteristics, description of the input, results of the application. Some elements of the methodology or software implementation are duplicated in different chapters, however in this way each application is a stand-alone chapter. Detailed description of each item may be found in the specific reference reports.

This reference report is related to other SYNER-G reference reports and deliverables, which are needed for a comprehensive understanding of the applications (e.g. Kaynia et al. 2011; Gehl et al. 2011; Franchin et al. 2011; Pinto et al. 2011; Weatherhill et al. 2011; Franchin et al. 2011; Pinto et al. 2012 among others).

1.2 SELECTION OF VALIDATION STUDIES AND BRIEF DESCRIPTION

The following case studies have been chosen for the application and validation in terms of applicability of the SYNER-G methodology and tools:

City of Thessaloniki in North Greece, located in a high seismicity area. The study area covers the municipality of Thessaloniki which is divided in 20 Sub City Districts as defined by Eurostat and Urban Audit approach. The case study includes the following elements: building stock (BDG), road network (RDN), water supply system (WSS) and electric power network (EPN). The networks are comprise by the main lines and components and cover the wider Metropolitan area. The internal functioning of each network is simulated and a connectivity analysis is performed. Moreover, specific interdependencies between systems are considered: EPN with WSS (electric power supply to pumping stations), RDN with BDG (road blockage due to building collapses), BDG with EPN and WSS (displaced people due to utility loss).
City of Vienna in Austria, located in a low seismicity area. The region of interest for the case study is the Brigittenau district, which is the 20th district of Vienna. A specific building identification procedure has been formulated to identify and inventory buildings that were considered in the case study. Both deterministic and probabilistic analyses have been performed. The EQvis software is used for the deterministic analysis, while the SYNER-G OOFIMSrunner performed the probabilistic analysis including buildings, water supply system, road and electric power network with specific interdependencies between them.

The gas system of L’Aquila in Italy. The medium-pressure portion of the L’Aquila gas system was selected. It is characterized by 3 M/R stations, 209 Reduction Groups, and pipelines at medium pressure, either made of steel or high density polyethylene. The network is comprised of 602 nodes and 608 links. A connectivity analysis is performed considering ground shaking and ground failure due to liquefaction.

The road network in Calabria region, Southern Italy. A data reduction process was performed in order to remove the irrelevant components at the regional scale. A pure connectivity analysis is performed considering 2,861 nodes and 5,970 edges of the network. The seismic hazard is modeled through 20 faults taken from the Italian DISS database.

The electric power network of Sicily. A capacitive study is performed, with power flow analysis that follows the analysis of short-circuit propagation, in which circuit breakers are active components playing a key role in arresting the short-circuit spreading. The substations are not modeled as vulnerable points; in fact, their full internal logic is modeled to account for partial functioning. The network is composed of 181 nodes and 220 transmission lines.

Hospital facility in Italy. The response of a regional health-care system is function of the hospital’s performance but also of other factors, among which the response of the road network is of primary importance. In this case study the main goal is to forecast the expected impact in terms of: a) victims that cannot be hospitalised; b) hospitals that cannot provide medical care to the victims; c) city/villages that are not served by a functioning hospital within a “reasonable” distance.

The harbor of Thessaloniki. The assessment of the systemic vulnerability of Thessaloniki’s port is performed. The port covers an area of 1,550,000 m² and trades approximately 16,000,000 tons of cargo annually, having a capacity of 370,000 containers and 6 piers with 6,500m length. In the case study, waterfront structures, cargo handling equipment, power supply system, roadway system and buildings are examined. In particular, for the systemic analysis, waterfront structures of a total 6.5 km length, 48 crane-nodes and two Terminals (one container and one bulk cargo) are considered. The interactions considered in the analysis are the supply of EPN to cranes and the road closures due to building collapses.
1.3 FRAGILITY CURVES

The fragility curves used in the applications are summarized in Table 1.1 for each vulnerable component. The fragilities curves are compiled and described in Reference Report 4 (Kaynia 2013).

<table>
<thead>
<tr>
<th>System</th>
<th>Component</th>
<th>Classification</th>
<th>IM Type</th>
<th>Fragility curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thessaloniki case study</td>
<td>EPN</td>
<td>transmission stations</td>
<td>open, mixed and closed-type with low level of building seismic design</td>
<td>PGA</td>
</tr>
<tr>
<td></td>
<td>WSS</td>
<td>pipelines</td>
<td>pipe material and diameter, joint type, soil type</td>
<td>PGV, PGD</td>
</tr>
<tr>
<td></td>
<td>BDG</td>
<td>RC buildings masonry buildings</td>
<td>see Table 2.1, Table 2.4</td>
<td>PGA</td>
</tr>
<tr>
<td></td>
<td>RDN</td>
<td>bridges</td>
<td>see Table 2.2</td>
<td>PGA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>road pavements</td>
<td>urban roads (2 lanes)</td>
<td>PGD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>roads (blockage due to buildings collapses)</td>
<td>road-building distance, building height</td>
<td>PGA</td>
</tr>
<tr>
<td>Vienna case study</td>
<td>BDG</td>
<td>RC buildings masonry buildings</td>
<td>see Table 3.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RDN</td>
<td>road pavements</td>
<td>urban roads (2 lanes), major roads (4 lanes)</td>
<td>PGD</td>
</tr>
<tr>
<td></td>
<td>WSS</td>
<td>pipelines</td>
<td>pipe material and diameter, joint type, soil type</td>
<td>PGV, PGD</td>
</tr>
<tr>
<td></td>
<td>EPN</td>
<td>transmission stations</td>
<td>open, mixed and closed-type</td>
<td>PGA</td>
</tr>
<tr>
<td>L’ Aquila case study (gas network)</td>
<td>GAS</td>
<td>pipes</td>
<td>pipe material, pipe diameter</td>
<td>PGV, PGD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M/R stations</td>
<td>un-anchored compressor stations</td>
<td>PGA</td>
</tr>
<tr>
<td>Transportation network in Italy</td>
<td>RDN</td>
<td>bridges</td>
<td>main road, secondary road</td>
<td>PGA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>road pavements</td>
<td>main road, secondary road</td>
<td>PGD</td>
</tr>
</tbody>
</table>
### Electric power network in Italy

| EPN   | Transformation/ distribution and distribution substations | microcomponents | PGA | see SYNER-G report D3.3 (Pinto et al. 2010) |

### Hospital facility in Italy

| HCS  | hospital facility (fault tree analysis) | non structural (architectural elements, basic installations, equipment/contents) & structural elements | PGA | see SYNER-G report D3.10 (Pinto et al. 2011b) |

### Harbor of Thessaloniki

<table>
<thead>
<tr>
<th>HRB</th>
<th>waterfronts</th>
<th>H&gt;10m, Vs=250m/s H&lt;=10m, Vs=250m/s</th>
<th>PGA, PGD</th>
<th>Kakderi and Pilitakis (2010), NIBS (2004)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cranes/ cargo handling equipment</td>
<td>non-anchored</td>
<td>PGA, PGD</td>
<td>NIBS (2004)</td>
</tr>
<tr>
<td>EPN</td>
<td>distribution substations</td>
<td>low voltage, non-anchored</td>
<td>PGA</td>
<td>NIBS (2004)</td>
</tr>
<tr>
<td></td>
<td>transmission stations</td>
<td>open, mixed and closed-type with low level of building seismic design</td>
<td>PGA</td>
<td>SRM-LIFE (2003-2007)</td>
</tr>
<tr>
<td>RDN</td>
<td>road pavements</td>
<td>urban roads (2 lanes)</td>
<td>PGD</td>
<td>NIBS (2004)</td>
</tr>
<tr>
<td>BDG</td>
<td>R/C and URM buildings</td>
<td>masonry: urm, stone/brick, low/medium height R/C: structural system, infill walls, building height, level of seismic design</td>
<td>PGA</td>
<td>Kappos et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>steel buildings</td>
<td>steel frame with unreinforced masonry infill walls, low-height</td>
<td>PGA</td>
<td>NIBS (2004)</td>
</tr>
</tbody>
</table>

### 1.4 MAIN RESULTS

The goal of the SYNER-G methodology, as demonstrated in the present case studies, is to assess the seismic vulnerability of an infrastructure of urban/regional extension, accounting for inter- and intra-dependencies among infrastructural components, as well as for the uncertainties characterizing the problem. A probabilistic approach is followed which samples earthquake events based on the methods and tools developed in SYNER-G. Each sampled event represents a single earthquake (shakefields method) and all systems are analyzed for each event. The results are then aggregated all over the sampled events. In this way, all the characteristics of each event (e.g., spatial correlations) are accounted for and preserved for the systemic analysis. For each system, selected Performance Indicators (PIs) are calculated based on the estimated damages and functionality losses of the different
Introduction and objectives

components. The overall performance of each network is expressed through the moving average \( \mu \) and moving standard deviation \( \sigma \) (averaged over simulations), as well as the Mean Annual Frequency (MAF) of exceedance of the PIs. Through the MAF graphs the annual probability of exceeding specific levels of loss can be defined and the loss for specific mean return period of the particular PI can be estimated. In some cases, correlation factors are estimated which relate the estimated damages of specific components with the system’s functionality.

Maps with the distribution of estimated damages (and/or non-functionalities due to direct damage, inter / intra dependencies, or propagated multi-functionalities) are given as averages all over the simulations or for specific earthquake events.
2 Application and validation study in the city of Thessaloniki

2.1 INTRODUCTION

The objective of the present study is to apply and validate the methods and tools developed in SYNER-G using the city of Thessaloniki as a case study. The main study area is the municipality of Thessaloniki, which is divided in 20 Sub City Districts as defined by Eurostat and Urban Audit approach. The case study includes the following elements: building stock (BDG), road network (RDN), water supply system (WSS) and electric power network (EPN). The networks are comprised by the main lines and components and cover the wider Metropolitan area. The internal functioning of each network is simulated. Moreover, specific interdependencies between systems are considered according to the SYNER-G methodology (Franchin et al. 2011): EPN with WSS (electric power supply to pumping stations), RDN with BDG (road blockage due to building collapses), BDG with EPN and WSS (displaced people due to utility loss).

For the seismic hazard, five seismic zones with $M_{\text{min}}=5.5$ and $M_{\text{max}}=7.5$ are selected based on the results of SHARE European research project (Arvidsson et al. 2010). Appropriate fragility curves are applied for the vulnerability assessment of each element at risk. For bridges and buildings (RC and masonry) new analytical fragility curves are applied, which have been developed in the framework of SYNER-G specifically for Thessaloniki area. A Monte Carlo simulation (MCS) has been carried out with 10,000 runs which samples earthquake events based on the methods and tools developed in SYNER-G.

For each system analyzed (EPN, WSS, BDG, RDN) we provide the description of the systemic vulnerability methodology and software implementation, the description of the system topology and characteristics and the input for the analysis and finally the results of the application. Selected Performance Indicators (PIs) are calculated based on the estimated damages and functionality losses of the different components. The overall performance of each network is expressed through the moving average $\mu$ and moving standard deviation $\sigma$ (averaged over simulations), as well as the Mean Annual Frequency (MAF) of exceedance of the PIs. The average loss is defined based on the moving average graph. The earthquake event that corresponds to a return period $T_m=500$ years is identified for each system and maps with the distribution of damages are produced for this event. The correlation of each component to the system PIs is estimated. This type of analysis is based on the results of each single event, and thus it preserves the information about systems’ topology and its behavior in case of spatial correlated damages (related to single earthquakes). Thus, it allows identifying the most critical elements for the functionality of each system (i.e., the damaged components that more closely control the performance of the network). To demonstrate the application of the socio-economic methodology in SYNER-G a shelter needs analysis has been applied. The shelter model simulates households’ decision-making and considers physical, socio-economic, climatic, spatial and temporal factors in addition to modeled building damage states and utility loss. Finally, a GIS-based accessibility modeling for earthquake case is implemented for shelter and healthcare services of Thessaloniki.
2.2 FRAGILITY CURVES FOR THESSALONIKI CASE STUDY

2.2.1 Fragility curves for RC buildings

Fragility curves are developed for the RC buildings of the Thessaloniki study area. The buildings are classified based on the structural system (infilled frames, frames with open ground storey and dual buildings), level of seismic design (1959 and 1984 seismic codes and Eurocode 8) and height (low-, mid- and high-rise buildings).

The geometry and reinforcement of buildings designed with the low- and medium-level seismic codes are taken from a set of buildings designed according to the Greek seismic codes of 1959 and 1984 (Kappos et al. 2003). High-level seismic code dual buildings are designed according to Eurocode 8 (CEN 2004b) for Medium Ductility Class and peak ground acceleration (PGA) 0.16g.

Fragility curves are constructed using PGA as intensity measure. For the two damage states of yielding and ultimate condition in flexure, the damage measure is the chord rotation at the member end. For the ultimate condition in shear, it is the shear force outside the plastic hinge or inside it considered then alongside the rotation ductility factor.

Deterministic estimates of these damage measures are obtained for each value of the excitation PGA via a static analysis per Part 3 of Eurocode 8 (CEN 2005b). Generic members considered in the models are limited to the interior columns and beams in wall-frame or frame systems and the walls of wall-frame systems. Vertical elements are taken as fixed at ground level, with negligible bending moments due to gravity loads.

Non-parametric fragility curves conditional on intensity measure are established point-by-point, from the probability that the random variable of damage measure demand exceeds the random variable of capacity. The seismic analysis gives the mean values of damage measure demands. Their variances are estimated from their coefficient of variation (CoV), based on comparisons of inelastic chord rotation demands in height-wise regular buildings to their elastic estimates (Panagiotakos and Fardis 1999; Kosmopoulos and Fardis 2007) and parametric analyses. The mean values of the corresponding capacities are determined according to Part 3 of EC8 (CEN 2005b). Their CoV reflects the uncertainty in the models and the scatter of material and geometric properties (Biskinis et al. 2004; Biskinis and Fardis 2010a, 2010b).

Fragility results are obtained separately for each member and storey. The fragility curve of a member at the ultimate damage state is taken as the maximum between two cases: plastic hinge in flexure or shear and of the part outside the hinge in shear. The probability that the building exceeds a damage state for a given PGA is taken as the highest among all the members. The parameters of the fragility curves are given in Table 2.1 and the fragility curves for dual buildings designed with high-level seismic code are shown in Fig. 2.1.
Table 2.1 Parameters of fragility curves for RC buildings in Thessaloniki

<table>
<thead>
<tr>
<th>Structural type</th>
<th>Seismic code</th>
<th>Height</th>
<th>Yielding</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Median (g)</td>
<td>St. deviation</td>
</tr>
<tr>
<td>Infilled frames</td>
<td>1959</td>
<td>L</td>
<td>0.25</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.30</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.41</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>1984</td>
<td>L</td>
<td>0.23</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.32</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.39</td>
<td>0.43</td>
</tr>
<tr>
<td>Pilotis</td>
<td>1959</td>
<td>L</td>
<td>0.12</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.12</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.27</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>1984</td>
<td>L</td>
<td>0.11</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.14</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.31</td>
<td>0.41</td>
</tr>
<tr>
<td>Dual</td>
<td>1959</td>
<td>L</td>
<td>0.12</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.15</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.21</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>1984</td>
<td>L</td>
<td>0.12</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.15</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.20</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>EC8</td>
<td>L</td>
<td>0.09</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.13</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.15</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Fig. 2.1 Fragility curves for dual buildings designed with high-level seismic code
2.2.2  Fragility curves for RC bridges

Fragility curves are constructed for 22 bridges, of the 60 that are located in the study area for which detailed construction drawings were available. They are classified based on the deck continuity and connection to the piers, constraint of the deck at the abutments, construction year and pier type, as shown in Table 2.2. The most appropriate among these fragility curves are assigned to the remaining bridges on the basis of their structural characteristics.

<table>
<thead>
<tr>
<th>Structural system</th>
<th>Type</th>
<th>Transverse translation at ends</th>
<th>Construction year</th>
<th>Pier Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearings, deck with expansion joints</td>
<td>B01</td>
<td>free</td>
<td>1984</td>
<td>multi-column</td>
</tr>
<tr>
<td></td>
<td>B02</td>
<td>free</td>
<td>1986</td>
<td>multi-column</td>
</tr>
<tr>
<td></td>
<td>B05</td>
<td>free</td>
<td>1985</td>
<td>multi-column</td>
</tr>
<tr>
<td></td>
<td>B09</td>
<td>free</td>
<td>1990</td>
<td>single-column</td>
</tr>
<tr>
<td></td>
<td>B22</td>
<td>free</td>
<td>1991</td>
<td>multi-column</td>
</tr>
<tr>
<td>Bearings, continuous deck</td>
<td>B03</td>
<td>free</td>
<td>1991</td>
<td>wall</td>
</tr>
<tr>
<td></td>
<td>B06</td>
<td>free</td>
<td>2002</td>
<td>multi-column</td>
</tr>
<tr>
<td></td>
<td>B17</td>
<td>free</td>
<td>1992</td>
<td>wall</td>
</tr>
<tr>
<td></td>
<td>B18</td>
<td>free</td>
<td>1992</td>
<td>wall</td>
</tr>
<tr>
<td>Monolithic connection, continuous deck</td>
<td>B04</td>
<td>restrained</td>
<td>2000</td>
<td>multi-column</td>
</tr>
<tr>
<td></td>
<td>B19</td>
<td>free</td>
<td>2004</td>
<td>wall</td>
</tr>
<tr>
<td>Monolithic connection and bearings, continuous deck</td>
<td>B07</td>
<td>restrained</td>
<td>2003</td>
<td>single-column</td>
</tr>
<tr>
<td></td>
<td>B08</td>
<td>restrained</td>
<td>2003</td>
<td>single-column</td>
</tr>
<tr>
<td></td>
<td>B15</td>
<td>restrained</td>
<td>2002</td>
<td>single-column</td>
</tr>
<tr>
<td></td>
<td>B20</td>
<td>free</td>
<td>1985</td>
<td>wall</td>
</tr>
<tr>
<td></td>
<td>B21</td>
<td>free</td>
<td>1985</td>
<td>wall</td>
</tr>
<tr>
<td>Single-span bridges on bearings</td>
<td>B10</td>
<td>free</td>
<td>1976</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>B11</td>
<td>free</td>
<td>1985</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>B12</td>
<td>free</td>
<td>1990</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>B13</td>
<td>free</td>
<td>1985</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>B14</td>
<td>free</td>
<td>1987</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>B16</td>
<td>free</td>
<td>1994</td>
<td>-</td>
</tr>
</tbody>
</table>

Fragility curves are constructed for two damage states: yielding of the piers and ultimate condition of the piers and the bearings. PGA is selected as the intensity measure. Damage measures are the peak chord rotation at the ends of piers and the deformation of the bearings.

Inelastic or elastic seismic displacement and deformation demands are estimated by 5%-damped elastic analysis, using the secant-to-yield-point stiffness of the piers and mean...
material strengths. Following the sequence of plastic hinge formation at pier ends, the shear forces are determined from the mean values of moment resistances.

The “rigid deck model” of Eurocode 8 (CEN 2005a) is used in the longitudinal direction of all bridges and in the transverse one of those with free transverse translation at the abutments. Modal response spectrum analysis is applied in the transverse direction of bridges with constrained transverse translation at the abutments. If the piers support the deck via bearings, the composite pier-bearing stiffness is used and the deck displacement is attributed to the pier and the bearing in proportion to their flexibilities.

The conditional probability of exceedance of each damage state is computed from the probability distributions of the damage measure demands and of the corresponding capacities. The seismic analyses give the median value of the damage measure of interest as a function of the intensity measure. The CoV values for the pier deformation demands for given excitation spectrum are based on Bardakis and Fardis (2011); those for creep and shrinkage are based on the scatter associated with the models used (CEN 2004a) and the natural dispersion of the variables they use. The expected values of the yield and ultimate chord rotation and the shear resistance of the piers and the corresponding CoVs are established from expressions based on experimental data (Biskinis and Fardis 2010a, 2010b, 2012; Biskinis et al. 2004). The CoV for the bearings are taken from the literature, alongside cyclic tests on elastomeric or lead rubber bearings tested at the Structures Lab of the University of Patras.

Fig. 2.2 Fragility curves for bridges with continuous deck on bearings

Fragility curves are constructed for each pier or bearing for seismic action separately in the transverse and the longitudinal direction of the bridge. The fragility curve of a component at a given damage state is taken as the worse of its possible conditions: namely, flexure or
shear failure for the piers, or rollover and shear deformation for bearings. The most adverse situation along the bridge is considered as follows: in the transverse direction of bridges with restrained transverse displacement at the ends due to deflection of the deck between the constraints at the abutments; in the longitudinal direction of bridges on bearings, due to the increase of thermal, creep and shrinkage displacements towards the abutments. The fragility curves for the bridge are determined by the most critical element, failure mode and direction at each value of PGA. As an example, the fragility curves for bridges with continuous deck supported on bearings are shown in Fig. 2.2. The parameters of the fragility curves for all bridges are given in Error! Not a valid bookmark self-reference.

Table 2.3 Parameters of fragility curves for RC bridges in Thessaloniki

<table>
<thead>
<tr>
<th>Type</th>
<th>Yielding Median (g)</th>
<th>Yielding St. deviation</th>
<th>Ultimate Median (g)</th>
<th>Ultimate St. deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>B01</td>
<td>0.43</td>
<td>0.44</td>
<td>0.16</td>
<td>0.80</td>
</tr>
<tr>
<td>B02</td>
<td>0.31</td>
<td>0.45</td>
<td>0.31</td>
<td>0.71</td>
</tr>
<tr>
<td>B03</td>
<td>0.88</td>
<td>0.42</td>
<td>0.26</td>
<td>0.92</td>
</tr>
<tr>
<td>B04</td>
<td>0.34</td>
<td>0.44</td>
<td>2.60</td>
<td>0.43</td>
</tr>
<tr>
<td>B05</td>
<td>0.23</td>
<td>0.45</td>
<td>0.29</td>
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</tr>
<tr>
<td>B06</td>
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<td>0.44</td>
<td>0.50</td>
</tr>
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<tr>
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<tr>
<td>B13</td>
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<td>B21</td>
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</tr>
<tr>
<td>B22</td>
<td>0.80</td>
<td>0.44</td>
<td>0.23</td>
<td>0.71</td>
</tr>
</tbody>
</table>

2.2.3 Fragility curves for unreinforced masonry buildings

Based on the inventory of masonry buildings in the Thessaloniki study area, fragility curves are developed for low-rise (two storeys) and mid-rise (four storeys) buildings with rigid or flexible floors. Prototype regular buildings are analysed. Both flexible (wood or steel beams) and rigid (concrete slab) floors are considered.
Peak ground acceleration is adopted as intensity measure. The five damage grades of the European Macroseismic Scale (Grünthal 1998) are used. The damage measure is a function of the percentage and the location of the surface area of the wall faces where failure of the masonry takes place according to a nonlinear biaxial failure criterion. In-plane and out-of-plane failure is considered.

Finite element models with shell elements are built for the prototype buildings. A nonlinear biaxial failure criterion based on the stresses at the two faces of the masonry wall (Karantoni et al. 1993) is used. The criterion is an extension of the four-parameter model by Ottosen (Ottosen 1977) for the failure of concrete under triaxial stresses. The parameters were obtained from experimental data for brick masonry.

Table 2.4 Parameters of fragility curves for masonry buildings in Thessaloniki

<table>
<thead>
<tr>
<th></th>
<th>Median (g)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DG1</td>
<td>DG2</td>
</tr>
<tr>
<td>Low-rise</td>
<td>Rigid floors</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Flexible floors</td>
<td>0.02</td>
</tr>
<tr>
<td>Mid-rise</td>
<td>Rigid floors</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Flexible floors</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Fig. 2.3 Fragility curves for low-rise (top) and mid-rise (bottom) masonry buildings with rigid (left) or flexible floors (right)

Static analysis is performed with an inverted triangular distribution of lateral forces. The horizontal components of the seismic action in the two main directions, $E_x$ and $E_y$, along the axes x and y, are combined as "$0.3E_x + E_y"$. The value of PGA at which a damage grade is attained is the median value of the corresponding damage curve. For simplicity, the standard deviation is taken equal to 0.6, as commonly assumed in fragility studies. The parameters of
the fragility curves for masonry buildings in the Thessaloniki study area are given in Table 2.4 and the curves are plotted in Fig. 2.3.

2.3 SYSTEMIC VULNERABILITY METHODOLOGY AND SOFTWARE IMPLEMENTATION

2.3.1 Systemic vulnerability methodology and performance indicators for EPN

A modern Electric Power Network (EPN) is a complex interconnected system that can be subdivided into four major parts (Pinto et al. 2011): Generation, Transformation, Transmission and Distribution, and Loads.

The electric power networks’ components (that can be considered vulnerable or not) can be grouped on the basis of five different vulnerability analysis scales of the network: Network, Station, Distribution system, Substations’ components (macro- and micro-components), and Line.

As in most of the systems, the analysis of an EPN in a seismically active environment can be carried out at two different levels. The first basic one focuses on connectivity only and can lead to a binary statement on whether any given node is connected with another node, specifically a source node, through the network (connectivity model). The other approach is power flow analysis which follows the analysis of short-circuit propagation (capacity model). This is the modeling approach adopted within the SYNER-G general methodology where the full internal logic of substations is modeled to account for partial functioning i.e., continued service with reduced power flow (Pinto et al. 2011).

The analysis performed in this application is based on connectivity only. Power flow analysis could not be applied, since detailed data about the substations layout and their micro- and macro-components are not available. The set of subsystems connecting (1) generator (non-vulnerable) to transmission substations (vulnerable), (2) transmission substations to distribution substations (non-vulnerable), and (3) distribution substations and demand nodes, are analyzed separately, in order to retrieve the functionality (isolated/non-isolated state) of each demand node. In this case study, distribution substations are not input, and thus transmission substations are directly connected to demand nodes.

Here, transmission substations, which are considered as vulnerable are connected with non-vulnerable transmission lines. A non-vulnerable transmission station (over-high voltage, 400kV) is considered as generator connected to the transmission stations (high voltage, 150kV-20kV). Demand nodes (non-vulnerable) are located at the centroid of each sub-city district (SCD). The interaction with the WSS is simulated through the connection of WSS pumping stations with the reference EPN load bus (here substation).

For the vulnerability analysis of the electric power transmission stations, the fragility curves proposed in SRM-LIFE (2003-2007) research project are used. The fragility curves for transmission substations are classified in 3 classes (open, mixed and closed-type).

2.3.2 Software implementation for EPN

The electric power network is made up of nodes and edges/lines connecting them. As a consequence, the EPN class is the composition of EPNedge and EPNnode classes, that are both abstract. In this connectivity analysis, the first one is the generalization of EPN Line...
Application and validation study in the city of Thessaloniki

(non-vulnerable), while the second one is the generalization of Generator (non-vulnerable), Transmission substations (vulnerable), distribution Substations (vulnerable) and EPN Demand nodes (non-vulnerable).

The following is the list of properties and methods of the EPN class, with the names following the naming convention adopted for variables in developing the prototype software, whereby multi-word names have no blank spaces in between words and the latter are separated by capitalizing the initial letter of each word.

**Properties**: (EPN) parent, line, demand, generator, substation, transmission, nGenerators, nTransmissions, nSubstations, nDemands, nodeSubType, nodeDepth, edgeLength, edgeDepth, ULweight, ONLYCONN, nodesPointers, edgesPointers, edges, nNodes, nEdges, adjacencyMatrix, incidenceMatrix, incidenceList, deadEnds, articPTS, bridges, nodePosition, nodeAltitude, nodeVs30, nodeSiteClass, nodeType, nodeIsVulnerable, nodeIMType, edgeCentroidPosition, edgeType, edgeVs30, edgeSiteClass, edgeDepth2GW, edgeLiqSusClass, edgeLandSusClass, edgeYieldAcc, vulnSites, MAF, states; (EPNNode) parent, position, altitude, type, Vs30, siteClass, isVulnerable, IMType, IDnode, states; (EPNEdge) parent, connectivity, centroid, L, Vs30, isVulnerable, IMType, material, siteClass, states; (Generator) refCells, parent, position, altitude, type, Vs30, siteClass, isVulnerable, IMType, IDnode, states; (Transmission) refCells, subType, parent, position, altitude, type, Vs30, siteClass, isVulnerable, IMType, IDnode, states; (Substation) refCells, parent, position, altitude, type, Vs30, siteClass, isVulnerable, IMType, IDnode, states; (DemandNodeEPN) refCells; (Line) refCells, parent, position, altitude, type, Vs30, siteClass, isVulnerable, IMType, IDnode, states.

**Methods**: analyzeEPN_ONLYCONN (EPN) ElectricPowerNetwork, anySDFS, buildSmAdjMatrix, buildSymIncList, checkStates, computePerformanceIndicator, connectedNodes, detectArticulationPoints, detectBridges, edges2Adjacency, edges2IncidenceList, edges2IncidenceMatrix, exportKMZ, exportSHP, findDeadEnds, isConnected, minPath, plotEPN plotEPNElements, plotEPNShakefield, plotPls, plotStateNetwork, retrieveLandSusEdges, retrieveLandSusNodes, retrieveLiqSusEdges, retrieveLiqSusNodes, retrieveSiteClassEdges, retrieveSiteClassNodes, retrieveVs30edges, retrieveVs30nodes, retrieveYieldAccEdges, retrieveYieldAccNodes, saveResults, saveStateNetwork, subNetwork, updatePureConnectivity; (EPNNode) EPNNode; (EPNEdge) EPNEdge; (Generator) Generator; (Transmission) Transmission, ranDamageState, IsEPNtransmissionDamaged; (Substation) Substation, ubDamageState, IsEPNsubstationDamaged; (DemandNodeEPN) DemandNodeEPN; (Line) Line.

### 2.3.3 Systemic vulnerability methodology and performance indicators for WSS

The vulnerability assessment of water supply network can be measured generally in four levels (Kakderi et al. 2011):

- Level I (Vulnerability Analysis)
- Level II (Connectivity Analysis)
- Level III (Flow Analysis)
- Level IV (Serviceability Analysis)
Within the seismic vulnerability analysis of a water system, water sources, water treatment plants, pumping stations, water storage tanks, canals, pipelines and tunnels are considered vulnerable components.

Water system is a network that can be modeled as a graph composed by the set of nodes connected by edge links with each other. The way these connections are formed determines how the vulnerability of each element influences the vulnerability of the network as a whole.

In the seismic vulnerability assessment the general aim of a connectivity analysis is to determine if a demand node is accessible from at least one supply node after the occurrence of a seismic event. It is important to note that if only the distribution part of the network is of concern, node functionality changes. In particular, considering only the distribution network, storage tanks become source nodes. Within the implemented software, the analysis is focused on the Infrastructure at the urban/regional scale and, hence, only the transmission system is modeled in the water supply network vulnerability analysis. For this reason, water sources, eventually served by pumping stations are considered as constant head source nodes, whereas storage tanks located inside the city are the demand nodes.

In flow analysis the functioning of a WSS is described analytically by a set of nonlinear equations. The set holds in so-called stationary conditions, i.e., it assumes constant end-user demands. This is a simplification, which is valid as long as the boundary conditions vary smoothly with time (quasi-stationary conditions). In seismic conditions this is not the case but the abrupt variation due to ruptures and leakages is soon replaced by a new stationary state. Solution of the above set of equations by a numerical algorithm allows verification of the serviceability levels in each end-user node.

The analysis performed in the present application is based only on connectivity (Level II). The system connecting tanks to demand nodes is analysed in order to retrieve the functionality (isolated/non-isolated state) of each demand node. Here, demand nodes of the system are connected with edges (pipelines). Storage tanks and pumping stations comprise the system's water sources. The only vulnerable elements of the system are the pipelines. For the vulnerability analysis of water pipelines, the fragility functions of ALA (2001) are used. The interaction with the EPN is simulated through the connection of WSS pumping stations with its specific reference EPN demand node.

**2.3.4 Software implementation for WSS**

The water supply system is made up of nodes and links connecting them. As a consequence, the WSS class is the composition of WSSnode and WSSlink abstract classes, of which the first is the generalization of the Pipe class, while the second is the generalization of the DemandNode, WaterSource and PumpingStation classes. In particular, the WaterSource abstract class is the generalization of the VariableHeadWaterSource and ConstantHeadWaterSource classes. An important interdependence considered within SYNER-G is between the WSS and EPN, in particular about the electric power supply to the pumping stations. If a pump serving a source node is not fed by the reference EPN node, then the pump itself is considered out of service and the relative WSS node removed from the system for the connectivity analysis.

The list of properties of the WSS class is given in detail in SYNER-G report D5.4 (Argyroudis et al. 2011). The following is the list of properties and methods of the WSS class, with the names following the naming convention adopted for variables in developing the prototype
software, whereby multi-word names have no blank spaces in between words and the latter are separated by capitalizing the initial letter of each word.

**Properties:** (WSS) parent, pipe, demand, source, pump, edgeDiameterNumber, nodeMinimalHead, nodeDepth, refEPNnode, edgeLength, edgeDiameter, edgeMaterial, edgeRoughness, edgeDepth, sourceHead, endUserDemand, interdependentEPN, hydraulicEquipment, belong2City, nodesCity, ULweight, ONLYCONN, nodesPointers, edgesPointers, edges, nNodes, nEdges, adjacencyMatrix, incidenceMatrix, incidenceList, deadEnds, articPTS, bridges, nodePosition, nodeAltitude, nodeVs30, nodeSiteClass, nodeType, nodesIsVulnerable, nodeIMType, edgeCentroidPosition, edgeType, edgeIsVulnerable, edgeIMType, edgeVs30, edgeSiteClass, edgeDepth2GW, edgeLiqSusClass, edgeLandSusClass, edgeYieldAcc, vulnSites, MAF, states; (WSSNode) parent, position, altitude, type, Vs30, isVulnerable, IMType, states; (WSSedge) parent, connectivity, centroid, L, Vs30, isVulnerable, IMType, material, siteClass, depth2GW, liqSusClass, landSusClass, yieldAcc, states; (ConstantHeadWaterSource) refEPNStation, head, parent, position, altitude, type, Vs30, isVulnerable, IMType, states; (PumpingStation) refSource, refEPNStation, parent, position, altitude, type, Vs30, isVulnerable, IMType, states; (DemandNode) minimalHead, refCells, parent, position, altitude, type, Vs30, isVulnerable, IMType, states; (Pipe) depth, D, roughness, parent, connectivity, centroid, L, Vs30, isVulnerable, IMType, material, siteClass, yieldAcc, states.

**Methods:** analyzeWSS_ONLYCONN, (WSS) WaterSupplySystem, anySDFS, buildSymAdjMatrix, buildSymIncList, checkStates, computeCovMean, computeCovMeanIS, computeCovMeanPerCity, computeCovMeanPerCityIS, computeDemand, computeFlow, computePerformanceIndicator, computePerformanceIndicatorPerCity, connectedNodes, detectArticulationPoints, detectBridges, discretizeEdges, draw3DWSS, drawNetworkAndSE, edges2Adjacency, edges2IncidenceList, edges2IncidenceMatrix, exportKMZ, exportSHP, findDeadEnds, getListOfLists, isConnected, minPath, plotPIs, plotPhysicalDamage, plotResults, plotStateNetwork, plotWSS, plotWSSElements, plotWSSShakefield, retrieveLandSusEdges, retrieveLandSusNodes, retrieveLiqSusEdges, retrieveLiqSusNodes, retrieveSiteClassEdges, retrieveSiteClassNodes, retrieveVs30edges, retrieveVs30nodes, retrieveYieldAccEdges, retrieveYieldAccNodes, saveResults, saveStateNetwork, setWSSnodesPerCity, subNetwork, updateConnectivity; (WSSNode) WSSnode; (WSSedge) WSSedge; (ConstantHeadWaterSource) ConstantHeadWaterSource; (PumpingStation) PumpingStation; (DemandNode) DemandNode; (Pipe) Pipe, computeLeakageArea, isBreakAndLeaksNumber, plotStatePipe.

### 2.3.5 Systemic vulnerability methodology and performance indicators for BDG

Within the object-oriented framework developed in SYNER-G (Franchin et al. 2011), each system is described as a class containing objects (i.e., instances) with similar features such as attributes and methods. Building related attributes and methodologies are part of the cell and region classes. Building cells are defined with a list of attributes (Gehl et al. 2011). Parts of them are initial parameters, which come from databases, and the other ones are derived from computation of the states of the overall system (performance indicators).
The following indicators are calculated at the cell level:

- **Building damage/collapse:**
  - Number of yielding buildings
  - Number of collapsed buildings

- **Building usability which is related to building damages:**
  - Number of non-usable buildings
  - Number of fully usable buildings
  - Number of partially usable buildings

- **Building habitability which is related to building usability, utility loss (water and electric power in this application) and weather conditions:**
  - Number of habitable buildings

- **Casualties:**
  - Number of deaths
  - Number of injuries

The building habitability results are used for the estimation of displaced persons in each cell which is considered in the shelter needs model.

### 2.3.6 Software implementation for BDG

Different methods are implemented in the SYNER-G tool to compute the different indicators required for the assessment of the building aggregates performances:

![Flowchart of the building class computation](image-url)
Project Building Census (BC) data into the cell; Project European Urban Audit (EUA) census data into the cell; Project Land Use Plan (LUP) data into the cell; Evaluate Building damages; Evaluate Casualties; Evaluate Building usability; Get Utility losses; Evaluate Building habitability; Get Building impacts on road network.

All these methods are chained in Fig. 2.1 and described in detail by Gehl et al. (2011).

2.3.7 Systemic vulnerability methodology and performance indicators for RDN

The analysis of a RDN can be carried out at different levels (see also Chapter 5):

- Level I (pure connectivity),
- Level II (traffic flow analysis),
- Level III (total losses due to direct damages, increased travel time, reduced activities in the economic sectors).

The modeling and the analysis of a transportation network for the purpose of seismic performance assessment rely on tools and methods of increasing complexity depending on the adopted approach. Level I studies require a simple description of the network in terms of a graph and analysis tools are limited to basic graph theory results. Level II and III studies require additional information and specialized algorithms for the determination of traffic flows on the congested, damaged network. In SYNER-G a level I analysis is performed, focusing on the functioning of the network in terms of pure connectivity. The network is represented as a directed graph, i.e., a graph in which all edges have a travelling direction, from node \(i\) to node \(j\). It is made up of nodes and links/edges connecting them.

Among the types of RDN nodes, Intersection nodes simply represent the summits of the graph that are used to define the edges that can link them: these nodes have no specific properties, except information on coordinates, altitude, soil type and so forth. TAZ nodes (i.e., Traffic Analysis Zones) are nodes that are defined around inhabited areas and they are used to evaluate the connectivity of a given neighborhood to others TAZs (i.e., they are used to build the origin –destination matrix): they have additional properties (such as number of households or the pointer to the reference cell) that can be used to evaluate traffic demand and connectivity loss for the associated cells. Finally, ExternalStation nodes are a type of TAZs that are not associated with the inhabited cells, but they are used to link the studied portion of road network to the ‘outside’ (i.e., definition of inward/outward traffic demand in the case of an open system).

The types of RDN edges are defined with respect to the physical properties of the road segments (i.e., bridges, tunnels, simple road segments, and roads in cuts, on embankment or on slope) and the different vulnerability models that may be used for each one of them (i.e., different damage mechanisms or intensity measures have to be considered for bridges or for road segments on unstable slope). Within each of these edge sub-classes, different typologies are also defined, depending on the material used, the soil type or the construction technique. Some other properties of edges include the pointers of the extremities (i.e., end and start nodes, as the graph is directed), the number of lanes or the number of ways (i.e., in order to generate two directed paths when there are two-ways edges). The definition of edges along with their extremities is used to build an adjacency and an incidence matrix, which are then used to describe the connectivity of the road network, and subsequently the accessibility of TAZ nodes.
When a TAZ node is associated with one or more inhabited cells, some dependency edges are created between the TAZ and the centroid of each cell. These lower order roads, which are not physically modeled in the main road network, are abstract edges that are necessary to compute the accessibility of the cells to the TAZ, and finally to the main road network.

In the framework of the Thessaloniki case-study, the evaluation of the performance of the road network system is carried out with a level I analysis, which is based on pure connectivity, as opposed to more elaborate analysis levels described in the SYNER-G report D5.2 (Pinto et al. 2012). The connectivity analysis is carried out between the TAZs and two performance indicators are used: the Simple Connectivity Loss (SCL) and the Weighted Connectivity Loss (WCL). Further details on the systemic vulnerability methodology and performance indicators of road network are given section 5.2.1 as well as in (Pinto et al. 2012).

2.3.8 Software implementation for RDN

Within the object-oriented framework developed in SYNER-G (Franchin et al. 2011), each system is described as a class containing objects (i.e., instances) with similar features such as attributes and methods. Similarly to other Network classes, a road network is made up of nodes and links/edges connecting them. As a consequence, the RDN class is the composition of the RDNnode and RDNedge abstract classes. The list of properties of the RDN class is given in section 5.2.2.

Additional developments have been implemented for Thessaloniki case study in order to simulate the road blockage due to collapsed buildings, the road blockage due to collapsed bridges and the aggregation of functionality losses for connectivity evaluation (see also SYNER-G report D6.1, Argyroudis et al. 2013). In particular, the following procedure is adopted to account for the functionality of the RDN edge.

![Fig. 2.2 Update procedure of the adjacency matrix](image-url)
During the simulation, an edge can be in the following states:

- Broken: 0 or 1 (direct physical failure)
- Blocked by Building: open, open for emergency, closed
- Blocked by Bridge: 0 or 1

These state variables appear in the output attributes of the simulations and they are used to update the adjacency matrix of the RDN class. This matrix represents all working edges that link two nodes by a 0, and the values are 1 otherwise. For each simulation, the values in the adjacency matrix are updated to account for the loss of functionality of some edges (i.e., connectivity analysis). Since here the edge can be disrupted by several causes, the logical tree presented in Fig. 2.2 is adopted to update the adjacency matrix (i.e., use of an OR gate).

### 2.4 THE CASE STUDY

The main study area is the municipality of Thessaloniki which is divided in 20 Sub City Districts as defined by Eurostat and Urban Audit approach. The case study includes the following elements: building stock (BDG), road network (RDN), water supply system (WSS) and electric power network (EPN). In the following, a short presentation of the seismic hazard of Thessaloniki’s area is given, and the topology and characteristics of each system are provided. Then, an overview of the input for the prototype software is given. The input sheets for epn, wss, bdg and rdn are organized within an Excel workbook. Representative results of the application are provided. The last two sections present the application for the accessibility analysis and the shelter demand analysis. Finally, the main conclusions of the validation study to the city of Thessaloniki are summarized.

#### 2.4.1 Seismic hazard

##### 2.4.1.1 Seismic source model

The study area is characterized by intense seismic activity with strong historical earthquakes of magnitudes larger than 6.0 (Papazachos and Papazachou, 1997). The most recent destructive earthquake occurred in the broader area of Thessaloniki on the Gerakarou-Stivos fault, along the Mygdonian graben (20 June 1978, M = 6.5). The mainshock caused extensive damage and loss of life in the metropolitan area of Thessaloniki and the surrounding villages.

Five seismic zones are selected for the seismic hazard input of the present case study (Fig. 2.3) as obtained by SHARE European research project (Arvidsson et al. 2010). 10,000 simulations are carried out sampling earthquake events for these zones based on a Monte Carlo approach.
2.4.1.2 Geotechnical maps

A detailed microzonation study has been conducted for Thessaloniki during the last years. A detailed model of the surface geology and geotechnical characteristics for site effect studies was generated. The resulted *geotechnical map* (Anastasiadis et al. 2001) was based on numerous data provided by geotechnical investigations, geophysical surveys, microtremor measurements, classical geotechnical and special soil dynamic tests (Pitilakis et al. 1992; Pitilakis and Anastasiadis 1998; Raptakis et al. 1994a; Raptakis et al. 1994b; Raptakis 1995; Apostolidis et al. 2004). The dynamic properties of the main soil formations have been defined from an extended laboratory testing including resonant column and cyclic triaxial tests (Pitilakis et al. 1992; Pitilakis and Anastasiadis 1998; Anastasiadis 1994).

For the purpose of the present study the map shown in Fig. 2.4 is used, where three soil formations are defined according to EC8 (CEN 2004b) classification scheme (i.e., A, B, C classes).

The *liquefaction susceptibility* of the study area is defined based on the classification scheme introduced by Youd and Perkins (1978) which is adopted in HAZUS (NIBS 2004) methodology. The classes (Very High, High, Moderate, Low, Very Low and None) are categorised on the basis of deposit type, age and general distribution of cohesionless loose sediments. The liquefaction susceptibility in case of Thessaloniki is defined based on information from previous studies (SRMLIFE 2003-2007). The zones are shown in Fig. 2.5.

The landslide hazard is not considered in the present case study as the *landslide susceptibility* in the study area is very low.
2.4.1.3 Seismic ground motion

Following the specification provided in SYNER-G report D2.13 (Weatherill et al. 2011), the ground motion prediction equation introduced by Akkar and Bommer (2010) is applied for the estimation of the ground motion parameters on rock, while the spatial variability was
modeled using correlation models provided by Jayaram and Baker (2009). For each site of the grid the averages of primary IM from the specified GMPE were calculated, and the residual was sampled from a random field of spatially correlated Gaussian variables according to the spatial correlation model. The primary IM is then retrieved at vulnerable sites by distance-based interpolation and finally the local IM is sampled conditional on primary IM.

To scale the hazard to the site condition different amplification methods are available in the SYNER-G prototype software: Present Eurocode 8 provisions, Eurocode 8 amplification as modified by Pitilakis et al. (2012), NEHRP, Choi&Stewart, context-specific. Only the amplification factors proposed in EC8 are used in the present application in accordance with the site classes that were defined in the study area.

For the liquefaction hazard the modeling approach of HAZUS (NIBS 2004) is adopted for the estimation of the permanent ground displacements, PGD, at the vulnerable sites. A detailed description of the entire hazard model adopted in the methodology and hence implemented in the SYNER-G prototype software can be found in Franchin et al. (2011) and Weatherhill et al. (2011).

2.4.2 General description, system topology and characteristics for EPN

The municipality of Thessaloniki is supplied by eight high voltage substations (150kV/20kV). Medium voltage lines (20 kV) give power to medium-voltage customers and distribution substations (about 1,500). Moreover, an over-high voltage substation connects the 400 kV grid with the 150 kV grid. Transmission lines (about 120 in number) are in their majority underground with a total length of 600 km (80 km overhead lines). Distribution stations’ voltages range between 630 KVA and 1630 KVA. They give power to low-voltage customers through an extremely extensive grid; underground at high-density load areas and overhead at low-density load areas. Fig. 2.6 illustrates a part of the electric power transmission grid of Greece and the study region.

The EPN is modeled as a directed graph. The electric power network for the case study is composed of 30 nodes and 29 edges (Fig. 2.7). The nodes are sub-divided into 1 generator, 8 transmission substations and 21 demand nodes. Only transmission substations are the vulnerable components. Fragility models for them are expressed in terms of peak ground acceleration (PGA). The fragility models for transmission substations are classified in three classes as it is described in section 2.5.1.

Edges are non-vulnerable transmission lines (underground and overhead) connecting the generator with the transmission substations and the transmission substations with the demand points.
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Fig. 2.6 Electric power transmission grid of Greece and study region

Fig. 2.7 Electric power network topology
2.4.3 Description of the input for EPN

The first two cells in the first row of epn sheet specify the number of edges (sides) and the number of nodes. It should be noted that the user has to input only one (directed) edge per couple of nodes. The UL weight field contains weights to estimate the total Utility loss for each building (UL), used in the socio-economic analysis for the estimation of shelter needs and health impacts. The UL weights for utility networks must sum up to 1.

The next rows, after the nodes keyword, specify in a standardized way (similar for all network/linelike systems) the nodes of the system. In particular the information to be provided for each node is in the following order: localization, site properties, functional and related to seismic damageability. Localization is given in terms of latitude and longitude in degrees and altitude above sea level in metres. The site properties fields are empty, as this information is given through the geotechnical map (GIS shapefile).

Functional information for the node of an EPN is the type of node (generator, transmission or demand) and the subtype of substations (generator or transmission). The next columns specify whether the node is vulnerable, and in this, which is the IM of the corresponding fragility model (e.g. PGA for transmission substations).

The next part of the sheet, specifies in a standardized way (similar for all network/line-like systems) the sides/edges of the system. In particular, the first two columns specify the edge connectivity (start and end nodes). The site properties are specified in terms of Vs30 (m/s) / Nspt. The fields that are left empty are read from corresponding GIS shapefiles. Functional information includes the edge typology (indicating the type of the line; overhead or underground), the voltage of the line (it is set to 0 for lines with transformer), and voltage ratio \[V(\text{start bus}) / V(\text{end bus})\]. As for the nodes, two columns specify whether the edge is vulnerable, and in this case, which is the IM(s) for the corresponding fragility model.

2.4.4 General description, system topology and characteristics for WSS

The city of Thessaloniki is supplied from various water sources (springs, wells, rivers). From the external aqueducts, the water is led to the main tanks and pumping stations. The treatment of raw water is confined only to its chlorination before the entrance to the distribution network. Water treatment units are placed at certain pumping stations, sedimentation tanks and wells.

The water supply system of the municipality of Thessaloniki includes 20 tanks with total capacity of 91,900m³. There is also a sedimentation tank of 8,000m³ capacity and a firefighting tank with total capacity of 2,100m³. The largest tank has a capacity of 10,000m³.

Steel pipelines with a total length of 71km comprise the main water transmission system. The distribution network has a 1,284.1km approximate length and a supply capacity ranging between 240,000 - 280,000m³/day.

The supplied customers are approximately 420,000 and the total supplied population about 1,000,000; 99% of which are domestic users. The supplied area is 55km². The elevation is ranging between 0-380m, and the water pressure between 2-5 bars. There are few areas in the municipality with independent water systems, supplied from local sources.

Due to the complexity and oldness of the system, along with the fact that in some regions the detailed topology of the system is not perfectly known, a simplified (yet realistic) model for Thessaloniki’s WSS is used for the analysis. The WSS for the case study is comprised of
477 nodes and 601 edges with total length of about 280 km (Fig. 2.8). The nodes are subdivided in demand nodes, pumping stations (costtankpump) and tanks (costtank); the latter considered as water sources for the system. The simulated network includes 437 demand nodes, 21 pumping stations and 11 tanks.

The WSS is modeled as a directed graph. Edges, that are the only vulnerable components in the network, include only pipelines. Fragility models are expressed in terms of peak ground velocity (PGV) and permanent ground displacement (PGD). Pipelines have 24 different diameter values (ranging between 500-3,000mm); their construction materials include asbestos cement, cast iron, PVC and welded steel.

![Fig. 2.8 Water supply system topology](image)

### 2.4.5 Description of the input for WSS

The first line in **wss** sheet specifies the number of edges (sides) and of nodes, 601 and 477, respectively, together with the number of different pipe diameters, the water daily equipment per capita, employed by the inhabitedArea class to automatically determine and assemble in demand nodes a water demand proportional to the population. The **want discretization** and following fields contain values used to discretize pipes specified between distant nodes into
a number of smaller pipes to improve the description of the vulnerability (each pipe-section is considered as a separate vulnerable element, with the IM evaluated at the section centroid).

The next rows, after the **nodes** keyword, specify in a standardized way (similar for all network/linelike systems) the nodes of the system. In particular the information to be provided for each node is in the order: localization, site properties, functional and related to seismic damageability. Localization is given in terms of latitude and longitude in degrees and altitude above sea level in metres. The site properties fields are empty as this information is given through the geotechnical map (GIS shapefile). Functional information for the node of a WSS is the type of node (demand node, costtank, pump or costtank), as well as the water head, the demand flow Q, the height of buildings and the depth which are required when a flow analysis is performed. The interaction with the EPN is simulated through the connection of WSS pumping stations with the reference EPN load bus. The next columns specify whether the node is vulnerable, and in this case, the IM of the corresponding fragility model.

The next part of the **wss** sheet, after the **sides** keyword, specifies in a standardized way (similar for all network/line-like systems) the sides/edges of the system. In particular, the first two columns specify the edge connectivity (start and end nodes). The site properties are specified in terms of Vs30, site class, depth to groundwater in feet, liquefaction and landslides susceptibility class, yield acceleration. The fields that are left empty are read from corresponding GIS shapefiles. Functional information includes the type (here only pipes), the diameter (mm), the material, the depth (m) and the $\gamma$ of Bazin (m$^{1/2}$). As for the nodes, two columns specify whether the edge is vulnerable, and in case it is, the IM for the corresponding fragility model (here PGV and PGD).

### 2.4.6 General description, system topology and characteristics for BDG

According to the 2011 census the municipality of Thessaloniki has a population of 322,240, while the Thessaloniki Urban Area has a population of 790,824. Furthermore, the Thessaloniki Metropolitan Area extends over an area of 1,455.62 km$^2$ and its population in 2011 reached a total of 1,006,730 inhabitants.

The study area comprises 20 **Sub-City Districts (SCD)** as they are defined by Eurostat through the European Urban Audit (EUA) approach (Fig. 2.9). The total population in this area is **376,589 inhabitants**.

The same subdivision is used for the definition the **Land Use Plan (LUP)** zones. The predominant use is residential (R), while some parts are characterized as commercial (C).

The building inventory in the study area is based on the inventory which was compiled during previous projects (Kappos et al. 2008), with the improvements and additions that took place within SYNER-G project (Tenerelli et al. 2012). The reference unit of the inventory is the building block. The building inventory comprises **2,893 building blocks** with **27,738 buildings**, the majority of which (25,639) are reinforced concrete (RC) buildings, while the rest (2,099) are masonry buildings.

The classification of RC buildings is described in Table 2.1 based on structural type (infilled frames, pilotis, dual), seismic code level and building height (low, medium or high rise). The classification of masonry buildings is described in Table 2.4 based on floor type (flexible or rigid) and building height (low or mid rise).
The classification of the buildings of the study area is illustrated in Fig. 2.10. Most of the buildings are either infilled dual RC systems while the majority of RC buildings are pre-1980 constructions and thus have been designed with low level of seismic code. The description of the building classes that are present in Thessaloniki inventory is given in Table 2.5.

Fig. 2.9 Sub-city districts (SCD) of Thessaloniki study area as defined by Urban Audit

Fig. 2.10 Classification of the buildings of the study area
2.4.7 Description of the input for BDG

The first lines of the bdg sheet specify the geometry (corner coordinates) of the study area, the number of mesh refinements and the habitability thresholds for bad and good weather conditions. In the following lines, the sub-city districts (SCD) and land use plan areas (LUP) geometry and associated indicators (population, average building height, volume per person, %empl. rate, % retail, % service, % other) are given. In next rows the building cencus (BC) areas are defined, in total 2,630 building blocks are included in the input. The geometry and associated information (number of buildings, percentage of buildings in each building class) are given for each BC.

2.4.8 General description, system topology and characteristics for RDN

Thessaloniki is extended along the seaside and consequently the urban road system is parallel and perpendicular to the sea. The roadway network of the urban area is rather
The road network for the case study is composed of 594 nodes and 674 edges (Fig. 2.11). The nodes are subdivided into 15 external nodes, 127 Traffic Analysis Zone (TAZ) centroids and 452 simple intersections. Edges, that are the only vulnerable components in the network, are subdivided into road segments and bridges, with fragility models expressed in terms of permanent ground displacement (PGD) and peak ground acceleration (PGA), respectively. New fragility curves have been developed for 22 bridges as described in section 2.3. For the other bridges, we selected the fragility curves from the aforementioned 22 bridges, which fit better to their typology characteristics. Edges are also classified as either principal roads (freeways and major arterials) or secondary roads (secondary arterials and collectors), based on their free flow speed and other functionality criteria.

The RDN is modeled as a directed graph and all edges have a travelling direction, from node i to node j. For this particular network, 495 edges are two-ways roads and 179 are one-way roads. Further information for roadway edges include the width of the road, the distance from buildings, the capacity and flow speed. The distance from buildings is based on data extracted through satellite maps as described in SYNER-G report D2.15 (Tenerelli et al. 2012) and on information from previous study (Argyroudis and Pitilakis 2011).
2.4.9 Description of the input for RDN

The first two cells in the first row of `rdn` sheet specify the number of edges (sides) and of nodes, 686 and 594, respectively. It should be noted that the user has to input only one (directed) edge per couple of nodes. If the corresponding road is a two-ways one, the second edge will be added automatically by the software. The want discretization and following fields contain values used to discretize too long edges into a number of smaller roads to improve the computation of roads' damage (each sub-segment is considered as a separate vulnerable element, with the IM evaluated at the segment centroid).

The next rows, after the nodes keyword, specify in a standardized way (similar for all network/line-like systems) the nodes of the system. In particular the information to be provided for each node is in the order: localization, site properties, functional and related to seismic vulnerability. Localization is given in terms of latitude and longitude in degrees and altitude above sea level in metres. The site properties fields are empty as this information is given through the geotechnical map (GIS shapefile).

Functional information for the node of an RDN is the type of node (either a TAZ, an external station or an intersection) and the type of TAZ (either CBD or non-CBD). The next columns specify whether the node is vulnerable, and in this case, the IM for the corresponding fragility model.

The next part of the sheet, specifies in a standardized way (similar for all network/line-like systems) the sides/edges of the system. In particular, the first two columns specify the edge connectivity (start and end nodes). The site properties are specified in terms of Vs30, site class, depth to groundwater in feet, liquefaction and landslides susceptibility class, yield acceleration. The fields that are left empty are read from corresponding GIS shapefiles. Functional information includes the edge typology (indicating the particular set of fragility functions to be used), the class (minor, principal or highway), the capacity in vph (vehicles per hour), the free flow speed in km/h, the number of ways (1 or 2) and the number of vulnerable elements for two ways roads (1 element to be shared or 2 distinct elements). As for the nodes, two columns specify whether the edge is vulnerable, and in this case, which is the IM(s) of the corresponding fragility model (i.e., PGA for bridges, PGD for road segments).

For the estimation of blockage due to building collapses the following properties are given: road width, building-road distance, and existence of adjacent buildings in one or two sides of the road edge. Finally for the estimation of blockage due to existence of overcross bridge (that is not modeled as an edge of the network) the overcross bridge type is given in the last column.

2.5 RESULTS

The analysis results as obtained from the plain MCS of 10,000 runs are presented in the following sections. The chosen number of runs have been shown to yield stable estimates for the considered PIs of each system.
2.5.1 Electric power network

Fig. 2.12 shows the moving average (mean) curve for ECL as well as the mean+stdv and mean-studv curves. The jumps present in the plots are located in correspondence of simulation runs/samples in which at least one demand node is disconnected, leading ECL to yield values greater than 0. At the end of the analysis (10,000 runs) the moving average is stabilized. Fig. 2.13 shows the MAF of exceedance for ECL. The ECL with mean return period Tm=500 years (λ=0.002) is 24% and the expected damages for the scenario with the maximum magnitude corresponding to the specific return period of ECL (out of the 10,000) are shown in Fig. 2.15. Functional and non-functional components (transmission substations and demand nodes – WSS pumping stations) for the event #6415 are mostly concentrated to the N-NE past of the city for the specific event.

Fig. 2.12 Moving average $\mu$, $\mu+\sigma$, $\mu-\sigma$ curves for ECL

Fig. 2.13 MAF curve for electric power network connectivity loss (ECL)
Fig. 2.14 Correlation of non-functional transmission substations to electric power network connectivity loss.

Fig. 2.15 Electric power network damages for an event (#6415 M=7.4, R=40km) that corresponds to ECL with Tm=500 years

Fig. 2.14 shows the level of correlation between the ECL and non-functional transmission substations. In this way the most critical components of the network can be defined in
relation with their contribution to the connectivity loss of the network. The majority of substations present high levels of correlation near or over 35%. This can be mostly attributed to the low level of redundancy of the network in combination to the substations vulnerability and distribution of PGA in average over all runs of the simulation.

2.5.2 Water supply system

Fig. 2.16 shows the moving average (mean) curve for WCL (Water Connectivity Loss) as well as the mean+stdv and mean-stdv curves. The jumps present in the plots are located in correspondence of simulation runs/samples in which at least one node is disconnected, leading WCL to yield values greater than 0. At the end of the analysis (10,000 runs) the moving average is stabilized. Fig. 2.17 shows the MAF of exceedance for WCL. In the same figure, the estimated MAF of exceedance curve for WCL when the interaction with electric power network is not considered in the analysis is compared. The interaction can be important; as an example the connectivity loss is increased from 1% to 1.8% for $\lambda=0.001$ ($T_m=1000$ years) when the connections of water pumping stations to EPN are included in the analysis.

Fig. 2.18 shows the level of correlation between the WCL and damages in pipelines as well as the non-functional EPN substations supplying the water pumping stations. The most correlated pipelines are concentrated along the coast where the liquefaction susceptibility is high and therefore damages due to permanent ground displacement are expected. Interestingly, a higher level of correlation is estimated for the EPN transmission substations. The highest value of 80% is attributed to component in the south east part of the city, where several pumping stations (connected to EPN) are located.

Fig. 2.19 shows the expected distribution of damages for the event with the highest magnitude that corresponds to connectivity loss (WCL=1.4%) with mean return period $T_m=500$ years ($0.002$ probability of exceedance). Only few broken pipes are observed, while the majority of non-functional pumping stations and not-connected demand nodes are accumulated at the S-SE part of the city.

![Fig. 2.16 Moving average $\mu$, $\mu+\sigma$, $\mu-\sigma$ curves for WCL](image)
Fig. 2.17 MAF curve for water connectivity loss (WCL) with and without interaction with electric power network (EPN)

Fig. 2.18 Correlation of damaged pipes and non-functional EPN transmission stations to water network connectivity
2.5.3 Buildings

Fig. 2.20, 2.21, 2.22 show the moving average (mean) curves for deaths, injuries and displaced persons as well as the mean+stdv and mean-stdv curves for these PIs. The values are given as percentages of the total population (790,824 inhabitants). At the end of the analysis (10,000 runs) the moving average is stabilized with an average value of 4 deaths, 11 injuries and 6,280 displaced people (in good weather conditions). This low fatality rate is reasonable in this case as the analysis averages the results over all possible magnitudes and epicentral distances, and the lower magnitude and longer distance events are certainly controlling the output.

Fig. 2.23, 2.24, 2.25 show the MAF of exceedance curves for deaths, injuries and displaced persons (as percentages of the total population). The expected deaths for $\lambda=0.002$ (mean return period $T_m=500$ years) are 201. The distribution of losses for an event that corresponds to this return period of deaths is shown in Fig. 2.27, 2.28, 2.29. For this event, the estimated losses are: 2,248 collapsed and 16,634 yielding buildings, 201 deaths, 492 injuries and 180,000 (in good weather) and 288,000 (in bad weather) displaced people. Fig. 2.26 shows the level of correlation between the damaged WSS and EPN components and the displaced people. It is observed that the correlation is higher with the EPN substations, which highlights the importance of the interaction between EPN loss and habitability.
Fig. 2.20 Moving average $\mu$, $\mu+\sigma$, $\mu-\sigma$ curves for deaths (average: 4)

Fig. 2.21 Moving average $\mu$, $\mu+\sigma$, $\mu-\sigma$ curves for injuries (average: 11)

Fig. 2.22 Moving average $\mu$, $\mu+\sigma$, $\mu-\sigma$ curves for displaced persons/good weather (average: 6280)
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Fig. 2.23 MAF curve for deaths

Fig. 2.24 MAF curve for injuries

Fig. 2.25 MAF curve for displaced persons
Fig. 2.26 Correlation of damaged EPN and WSS components to displaced people
Fig. 2.27 Distribution of estimated damages (collapsed and yielding buildings) into cells of the study area for an event (#1488, M=5.5, R=24 km) that corresponds to death rate with Tm=500 years
Fig. 2.28 Distribution of estimated casualties (deaths, injuries) into cells of the study area for an event (#1488, M=5.5, R=24 km) that corresponds to death rate with Tm=500 years.
Fig. 2.29 Distribution of estimated displaced persons in good (up) and bad (down) weather conditions into cells of the study area for an event (#1488, M=5.5, R=24 km) that corresponds to death rate with Tm=500 years
2.5.4 Roadway network

Fig. 2.30 shows the moving average (mean) curves for SCL (left) and WCL (right), as well as the mean+stdv and mean-stdv curves for the two PIs. The figures indicate that the expected value of connectivity loss given the occurrence of an earthquake is higher for WCL than for SCL, as expected. This is because WCL takes into account not only the existence of a path between two TAZs, but also the increase in travel time due to the seismically induced damage suffered by the RDN. The jumps present in the plots are located in correspondence of simulation runs/samples in which at least one TAZ node is disconnected, leading SCL and WCL to yield values greater than 0. At the end of the analysis (10,000 runs) the moving average is stabilized.

Fig. 2.30 Moving average \( \mu, \mu+\sigma, \mu-\sigma \) curves for SCL (left) and WCL (right).

Fig. 2.31 shows the MAF of exceedance curves for SCL and WCL. As expected, weighting the computation of connectivity loss with the path travel times yields higher values of exceedance frequency. Fig. 2.32 compares the estimated MAF of exceedance curve for WCL when the road blockage due to collapsed building is not considered in the analysis. The interaction with building collapses can be important especially for mean return periods of WCL higher than 500 years (\( \lambda=0.002 \)). As an example the connectivity loss is increased from 20% to 33% for \( \lambda=0.001 \) (\( T_m=1000 \) years) when the building collapses are included in the analysis.

Fig. 2.33 and Fig. 2.34 show the level of correlation between the WCL and the distribution of damages in bridges and road blockages respectively. In this way the most critical segments can be defined in relation with their contribution to the connectivity loss of the network. The most correlated bridges are: interchanges K17 and K18 of the ring road, interchange of Monastiriotou avenue with railway (Mytilinakia), interchange of Monastiriotou avenue with Dendropotamou avenue, bridge of Anthemountas river on the airport access road. These bridges present a high risk of failure due to their vulnerability (old, simple span bridges) and the high values of PGA. The most correlated blocked roads are mainly in the historical center of the city, where the vulnerability of buildings is higher and the road to building distance is shorter. Several road segments in the city center and the SE part of the study
area present a medium correlation due to building collapses. Few roads near the coast which are subjected to ground failure to liquefaction are also highly correlated to the network connectivity.

Fig. 2.35 shows the expected distribution of damages for the event with the highest magnitude that corresponds to connectivity loss (WCL=18%) with mean return period T\text{m}=500 years (0.002 probability of exceedance). For this event no blockages are expected due to building collapses. However, seven bridges will be severely damaged and few road blockages due to damage of overpass bridges are expected in the main road network. Damages due to liquefaction are concentrated in the airport access roads.

![Fig. 2.31 MAF curve for simple (SCL) and weighted (WCL) connectivity loss.](image)

![Fig. 2.32 MAF curve for weighted connectivity loss (WCL) for the road network of Thessaloniki, with and without interaction with building collapses](image)
Fig. 2.33 Correlation of broken edges (bridges) to road network connectivity (PI=WCL)

Fig. 2.34 Correlation of blocked by buildings edges to road network connectivity (PI=WCL)
2.6 ACCESSIBILITY ANALYSIS

GIS-based accessibility modeling for earthquake case is implemented on healthcare and shelter services of Thessaloniki by using isochrone-based and zone-based techniques considering the results of the RDN analysis. More details about these techniques are given in SYNER-G report D6.1 (Argyroudis et al. 2013). The implementation of the case study consists of three major steps:

- Data acquisition and integration, which includes:
  - The main road network of Thessaloniki as described in section 2.6.
  - The supply locations of health services and shelters with area greater than 1 hectare.
  - The demand locations described by the administrative districts of Thessaloniki (SCDs of Urban Audit, see section 2.6).
  - The average road closure probabilities over 10,000 simulations due to building collapses, soil liquefaction, bridge damages and overpass bridge collapses (see section 2.6).

- Transportation network based traveling cost calculation. For the road segments that have no road closure probability, an average speed of 30km/h is assigned for the major roads (freeways and main arterials), and 25km/h is assigned for other minor...
road classes (secondary arterials, primary collectives, and secondary collectives). For the road segments that have road closure probability scores, the scores are first normalized into 0 and 1 interval, then classified into 4 categories which are; “<=0.25%”, “0.25%-0.50%”, “0.50%-0.75%” and “>=1%” and then used in calibration of the transportation network costs. For the road segments that have “<=0.25%” road closure probability, transportation network costs are decreased by 25%. For the road segments that have “0.25%-0.50%”, road closure probability, transportation network costs are decreased by 50%. For the road segments that have “0.50%-0.75%” road closure probability, transportation network costs are decreased by 75%. Finally for the road segments that have “>=1%” road closure probability, transportation network costs are decreased by 100% which means the road segment is totally closed.

- Accessibility modeling and visualization. Health service accessibility is calculated based on 3 different accessibility modeling techniques:

  o Isochronal-based technique (travel time measure) where the accessibility measures are represented in terms of isochronal polygons, which are also known as the catchment or service area polygon boundaries. These boundaries connect equal travel time or distance points away from one or more reference points (e.g., supply or demand). They are calculated based on either constant average speeds depending on the road classification or unconstrained Euclidean distance (straight-line/bird-flight based distances) such as buffer, voronoi (thiessen) polygons without considering the transportation network. When an origin is defined as a reference point such as a demand or supply location, isochronal polygon boundaries can be drawn by connecting all points in all directions for an equal threshold of time or distance. According to the results, most of the study area has 10 minutes or less for health service accessibility. However, there are some partial areas in the north-west and south-east regions that have over 10 minutes health service accessibility (Fig. 2.36).

  o Zone-based technique (travel time measure) where the travelling cost calculation between supply and demand points is based on the zone (SCDs) centroids. It has the advantage of easier comparisons of accessibility scores between the bordered zones. According to the results, the SCDs 0, 11, 12, 13, 14, 18 have the lowest health service accessibility and the SCDs 2, 7 have the highest accessibility (Fig. 2.37). This technique is also used for the shelter accessibility (Fig. 2.38).

  o Zone-based technique (gravity measure), where the classification of importance (global value score) of hospital services is also accounted in the travelling cost calculation. According to the results the SCDs 0, 10, 11, 12, 13, 14, 18 have the lowest health service accessibility and the SCDs 2, 4, 7, 16, 19 have the highest accessibility (Fig. 2.39).

In GIS environment, it is also possible to define shortest routes between supply and demand points as in Fig. 2.40. The results are useful in terms of determination of the shortest route segments and required time cost in that segment by considering the costs in the transportation network.
Fig. 2.36 Combined isochronal accessibility

Fig. 2.37 Health service accessibility as a travel time measure in zone based technique
Fig. 2.38 Shelter accessibility as a cumulative travel time measure in zone based technique.

Fig. 2.39 Health service accessibility as a gravity measure in zone based technique.
2.7 SHELTER DEMAND ANALYSIS

To demonstrate the application of the socio-economic methodology in SYNER-G a shelter needs analysis has been applied in the Thessaloniki study area. The goal here is to demonstrate how such a framework can be used as a communication tool for decision makers in disaster risk management through the interactive modeling of indicator weights or complementing the existing system of indicators with additional available data (e.g., for the assessment of additional vulnerability dimensions). 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 modeled building damage states. A group of proposed socio-economic indicators were harmonized for Thessaloniki based on data available for Europe from the EUROSTAT Urban Audit Database.

In the Thessaloniki application, a new advancement to shelter estimation methodology was explored through three types of key inputs: (1) the “habitability” of buildings which combines inputs from the physical models (building usability, utility loss and climate factors) to provide information on the habitability of a building and can be used as a better determinant in influencing the decision to evacuate than building damage alone; (2) GIS-based shelter accessibility analysis as an input to the shelter seeking model – as discussed in the
preceding section of this report; and (3) a multi-criteria decision model for implementing a shelter-seeking logic model based on complex socio-economic factors which ultimately lead to the decision to evacuate and seek public shelter. These three inputs are combined into a dynamic shelter model and software tool developed within the SYNER-G platform to provide stakeholders an interactive framework in decision-making process for shelter planning and preparedness as well as resource allocation. The multi-criteria framework is described schematically in Fig. 2.41 as composed of the three measures: a) Uninhabitable Building Index (UBI), b) Lack of Resistance to Evacuation (LRE) and c) Shelter Seeking Index (SSI). More details on these models are given in SYNER-G Reference Report 5 (Khazai 2013) and report D6.1 (Argyroudis et al. 2013).

Fig. 2.41 Hierarchical multi-criteria framework to describe shelter needs

The first step in the decision to evacuate after an earthquake is based on the structural stability of a building and functional lifeline structures, such as access to water and electric power services. Weather conditions can further aggravate potential displacement from damaged buildings with disrupted lifeline services. The “displaced persons” model provides an estimate of proportion of persons in habitable and uninhabitable buildings using the following inputs (Fig. 2.42a):

- Building Usability (building structural damage which leaves the building unusable, partially or fully usable depending on the level of damage and possibility of repairs)
- Utility Loss in water supply and electric power
- Weather conditions (which determine the tolerance to utility loss)

The decision to evacuate one’s home after an earthquake and to utilize public shelter is correlated with a variety of social, economic and demographic factors. The EUROSTAT Urban Audit data has been analyzed for 34 indicators collected for 20 SCD of Thessaloniki. The desirability to evacuate was ranked for each SCD (Fig. 2.42b) based on specific indicators (i.e., Proportion of dwellings lacking basic amenities; Proportion of non-
conventional dwellings; Lone-parent households with children aged 18 or under; Lone pensioners; Proportion of total population aged 0-4; Proportion of total population aged 75 and over).

Not all displaced population will seek public shelter, and some may find alternative shelter accommodations (rent motel rooms or apartments), stay with family and friends, or leave the affected area. The desirability to seek public shelter was ranked for each SCD (Fig. 2.42c) based on specific indicators (i.e., Ratio of economically inactive residents; Ratio of unemployed residents; Number of residents born abroad; Residents not EU Nationals and citizens of a country with a very high or high HDI; Residents who are not EU Nationals and citizens of a country with a medium or low HDI; Prop. of working age population qualified at level 1, 2, 3, 4, 5 and 6 ISCED). The proximity and ease of access of shelter locations might be key criteria for these households whose decision of leaving is not founded on aspects of vulnerability but on individual preferences (Fig. 2.42d).

The integrated shelter needs model developed here is based on a multi-criteria decision theory (MCDA) framework which allows the bringing together of parameters influencing the physical inhabitability of buildings, with social vulnerability (and coping capacity) factors of the at-risk population to determine as well as external factors to determine the desirability to evacuate and seek public shelter. The multi-criteria framework is composed of two main criteria: overall population at risk of being displaced after an earthquake (DPI) and the proportion of this population likely to seek public shelter (SSI). The Displaced Persons Index (DPI) is given as occupants in uninhabitable buildings (UBI) amplified by external and internal factors related to desirability to evacuate (Fig. 2.42e).

The total demand for public shelter for a particular location (i.e., city district) can be described as a product of the population at risk of being displaced (D1, D2 and D3) to the population likely to seek public shelter (D4) (Fig. 2.42f).
Application and validation study in the city of Thessaloniki

(a) Uninhabitable Buildings (Bad Weather Conditions)

SCD_WGS84
Uninhabitable Buildings Goal
- 0.000000 - 0.051637
- 0.051638 - 0.140218
- 0.140219 - 0.292172
- 0.292173 - 0.552840
- 0.552841 - 1.000000

(b) Desirability to Evacuate Criteria

SCD_WGS84
Desirability to Evacuate Goal
- 0.292000 - 0.324000
- 0.324001 - 0.368000
- 0.368001 - 0.439000
- 0.439001 - 0.496000
- 0.496001 - 0.599000

(c) Shelter Seeking Index (SSI)

SCD_WGS84
Shelter Seeking Index Goal / none
- 0.198000000 - 0.249000000
- 0.249000001 - 0.346000000
- 0.346000001 - 0.469000000
- 0.469000001 - 0.661000000
- 0.661000001 - 0.796000000

without considering shelter accessibility
Application and validation study in the city of Thessaloniki

Fig. 2.42 Ranking of different indexes for shelter demand analysis in Thessaloniki

(d) Shelter Needs Index (SNI)
SCD_WGS84
SCD_WGS84.SNI_Ac / none

(e) Displaced Persons Index (DPI)
SCD_WGS84
SCD_WGS84.DPI

(f) Shelter Needs Index (SNI)
SCD_WGS84
SCD_WGS84.SNI / none

with considering shelter accessibility
2.8 CONCLUSIONS

The SYNER-G methodology has been applied to the city of Thessaloniki, the second largest city of Greece, an area characterized by intense seismic activity. The main study area is the municipality of Thessaloniki which is divided in 20 Sub City Districts as defined by Eurostat and Urban Audit approach. The case study includes the following elements: building stock (BDG), road network (RDN), water supply system (WSS) and electric power network (EPN). New analytical fragility curves are developed for buildings (RC/masonry) and bridges based on the inventory of Thessaloniki area. Yielding and ultimate damage states are considered with PGA as intensity measure.

Buildings and networks as well as the seismic hazard acting upon them are modeled in the SYNER-G prototype software through the object-oriented paradigm. Five seismic zones have been selected based on SHARE European research project. A plain Monte Carlo simulation (MCS) has been carried out sampling earthquake events for these zones and computing selected performance indicators (PIs) for each system. A connectivity analysis has been performed for EPN, WSS and RDN considering specific interdependencies between systems according to the SYNER-G methodology: EPN with WSS (electric power supply to pumping stations), RDN with BDG (road blockage due to building collapses), BDG with EPN and WSS (displaced people due to utility loss). Results coming from analyses carried out indicate the important role of interdependencies in the overall performance of the networks. The estimated losses are much higher when interactions are considered.

The overall performance of each network is expressed through the moving average $\mu$ and moving standard deviation $\sigma$ (averaged over simulations), as well as the Mean Annual Frequency (MAF) of exceedance of the PIs. The average loss is defined based on the moving average graph. Through the MAF graphs the annual probability of exceeding specific levels of loss can be defined and the loss for specific mean return period of the particular PI can be estimated. The earthquake event(s) that correspond to a particular return period (i.e., 500 year) are identified and maps with the distribution of damages are produced for this event(s). Correlation factors are estimated which relate the estimated damages of specific components with the system’s functionality. This type of analysis is based on the results of each single event, and thus it preserves the information about systems’ topology and its behavior in case of spatial correlated damages (related to single earthquakes). Thus, it allows identifying the most critical elements for the functionality of each system (i.e., the damaged components that more closely control the performance of the network).

A GIS-based accessibility modeling for earthquake case has been implemented for shelter and healthcare services of Thessaloniki. It is a representative example, without considering the whole city and all networks. Nevertheless, it is clearly shown that the methodology, which has been developed can be an important tool for seismic risk management purposes, before, during and after disasters. GIS based accessibility modeling can directly provide a vital support to disaster managers in terms of accessibility, location/allocation of available resources and service/catchment related issues.

To demonstrate the application of the socio-economic methodology in SYNER-G a shelter needs analysis has been applied. The shelter model simulates households’ decision-making and considers physical, socio-economic, climatic, spatial and temporal factors in addition to modeled building damage states and utility loss. From the analysis, different SCDs of Thessaloniki are identified as “Hot Spots” for shelter needs. These results are supporting an efficient planning of shelter allocation.
3 Application and validation study in the city of Vienna

3.1 INTRODUCTION

The city of Vienna is located in the North-Eastern part of Austria. It is the capital of Austria with a population of about 1,697,982 people. The city of Vienna is placed east of the Alps, at the west end of the tertiary Wiener Beckens. Three main geological formations can be identified:

- Brash and sand from the river Danube
- Loose rock – tertiary loose rock from the Vienna basin
- Solid rock from the flysch zone and the limestone alps

There is a system of north-south aligned faults and cracks that goes through the city of Vienna. The majority of seismic risk in Austria is associated with the Vienna transform fault zone, which runs through the eastern part of Austria beneath the city of Vienna and surrounding areas (Achs et al. 2010).

![Fig. 3.1 Historic seismicity of Austria](image)

The region of interest in the city selected for the case study is the Brigittenau district, which is the 20th district of Vienna. It is located north of the central district, north of Leopoldstadt on the same island area between the Danube and the Danube Canal. Brigittenau is a heavily populated urban area with many residential buildings.

The reasons for the choice of this particular area can be summarized as follows:

- The district consists of various types of buildings, with construction practices that start from 1848 up until recently (Fig. 3.2).
The topic of transportation is covered even in this relatively small area as there are railroads/railway stations, underground and tramway lines as well as bus lines and numerous very frequently used bridges across the Danube.

There are numerous essential facilities like fire stations, police stations, schools, ambulance stations, an important hospital, the Millennium Tower (one of the tallest buildings in Vienna), etc.

There is a huge amount of data available for the whole district (lifelines, essential facilities, etc.) (Fig. 3.3).

![Fig. 3.2 Brigittenau district in the city of Vienna (left classification of the building stock according to the year of construction (right)](image1)

![Fig. 3.3 Overview of the transportation networks in the considered area of interest](image2)

A deterministic and a probabilistic analysis have been performed in the area of interest. The EQvis software has been used for the deterministic analysis, while the OOFIMS runner performed the probabilistic analysis. EQvis has been developed within SYNER-G and
provides a platform for performing deterministic earthquake simulations as well as various other tools for pre and post processing of the input and output data of both the deterministic and probabilistic (OOFIMS) analyses. The objective of the present application is to apply and validate the functions of EQvis platform. Next sections present the input data and the results obtained for both calculations.

3.2 EQVIS DETERMINISTIC ANALYSIS: INPUT DATA

3.2.1 EQvis: a consequence based risk management platform

EQvis is an advanced seismic loss assessment, and risk management software which is based on the Consequence-based Risk Management (CRM) methodology. CRM provides the philosophical and practical bond between the cause and effect of the disastrous event and mitigation options. It enables policy-makers and decision-makers to ultimately develop risk reduction strategies and implement mitigation actions (Schäfer et al. 2013). In EQvis, a wide range of user-defined parameters are introduced. The breadth of user-defined parameters enables emergency planners to model a virtually unlimited number of scenarios.

EQvis is based on the open-source-platform MAEviz, developed by the Mid-America Earthquake (MAE) Center and the National Center for Supercomputing Applications (NCSA) (MAEviz).

It has an open-source framework which employs the advanced workflow tools to provide a flexible and modular path. It can run over 50 analyses ranging from direct seismic impact assessment to the modeling of socioeconomic implications. It provides 2D and 3D mapped visualizations of source and result data and it provides tables, charts, graphs and printable reports for result data. It is designed to be quickly and easily extensible.

3.2.2 The Building Identification Procedure

The building identification procedure has been formulated to identify and inventory buildings that will be considered in the present case study (FEMA 2002). The procedure can be implemented relatively quickly and inexpensively to develop a list of potentially vulnerable buildings without the high cost of a detailed seismic analysis of individual buildings. The inspection, data collection, and decision-making process typically will occur at the building site, taking an average of 15 to 30 minutes per building (30 minutes to one hour if access to the interior is available). The main purpose of this procedure is to identify and categorize buildings in a relatively big area. The output of this procedure is a fact sheet for every building, which contains all the essential information with respect to earthquakes and the overall condition of the building. The Data Collection Form includes space for documenting building identification information, including its use and size, a photograph of the building, and documentation of pertinent data related to seismic performance.

Buildings may be reviewed from the sidewalk without the benefit of building entry, structural drawings, or structural calculations. Reliability and confidence in building attribute determination are increased, however, if the structural framing system can be verified during interior inspection, or on the basis of a review of construction documents. The BIP procedure is intended to be applicable nationwide, for all conventional building types. Bridges, large towers, and other non-building structure types, however, are not covered by the procedure.
Completing the Building Identification Protocol

The purpose of the chapter is to give instructions how to complete the Building Identification Protocol for each building screened, through execution of the following steps:

a) Verifying and updating the building identification information.
b) Walking around the building to identify its size and shape and looking for signs that identify the construction year.
c) Determining and documenting occupancy.
d) Determining the construction type.
e) Identifying the number of persons living/working in the building.
f) Characterizing the building through the plan view and determining the distance to traffic area.
g) Characterizing the building elevation; using the laser telemeter to define building height; identifying soft stories or added attic space.
h) Identifying façade elements inclusively number of windows and doors.
i) Determining non-structural members.
j) Determining the overall condition of the building.
k) Noting any irregularities/anomalies.
l) Taking pictures with the digital camera.

All these steps have to be done carefully. Each step is now explained in detail.

a) Verifying and updating the building identification information.

This is the first step in the whole procedure. When you arrive at the site you first have to check if this is the building you want to examine. If this is the case start filling the first field in the protocol. Start with date, name and time and work your way down.

![Fig. 3.4 Verifying and updating the building identification information](image)

b) Walking around the building to identify its size and shape and looking for signs that identify the Construction year.

At first the building should be looked at to identify its size and shape and to get a first impression of the building. The construction year of a building can be determined if there is a sign at the facade of the building. If there is not such a sign, and the construction year cannot be determined, the field Construction Year should be empty. It is much better to analyse this building later, if needed, than to have a wrong construction year.
c) Determining and documenting occupancy.

This is a very important field. It describes the general usage of the building, like apartment building, school, kindergarten, hospital, office building, etc. If the building usage is not limited to one category the percentage of the usage categories have to be identified. Example: Apartments (70%), Offices (30%).

d) Determining the construction type.

The construction type can be hard to identify in the field and without appropriate additional knowledge. What can be determined easier is the construction material. It is often very helpful if one knows the year of construction, because in certain periods, construction materials were very similar. It can also be helpful to have a look into the building, if possible. Often the interior walls can give clues as to what building type is present. Sometimes it also helps to get into the basement, because the walls are not always covered in basements.

e) Identifying the number of persons living/working in the building.

This is a very important step in the whole procedure. In order to find the possible persons, which can be in danger during an earthquake, one has to know how many people are living/working in a building. The number of dwelling units can easily be determined in the entrance area of a building by looking at the number of door bells or the number of mail boxes. All dwelling units, even not used ones, should be counted. The next field addresses the number of people living or working in areas not depicted as dwelling units like shops at the basements, cafes, etc. The number can only be approximated, but this number should depict the maximum number of persons that can stay/work in the building. An Example: There is a building with a café in the basement. This café has 3 employees working there and about 10 tables, where 3 persons can sit. Even when at the time of the screening process the café was empty the number to be filled has to be 33. (3 workers + max. 30 guests).
f) Characterizing the building through the ground plan and determining the distance to traffic area.

The characterization of the building through the ground plan can mostly be made with a plan of the city. There are three questions to be answered: Is the building a Corner Building? Are there any adjacent buildings? Does the building have a rectangular ground plan?

![Plan views of various building configurations showing plan irregularities](image)

Fig. 3.6 Plan views of various building configurations showing plan irregularities; arrows indicate possible area of damage (FEMA 2002)

The distance to traffic area means the lowest distance between building and street. Parking areas and sidewalks do not count as traffic areas and should not be considered. The purpose of this distance is to know whether street can be blocked by building debris or not.
g) Characterizing the building elevation; Using the laser telemeter to define building height; identifying soft stories or added attic space.

The easiest fact to determine is the number of floors. This number represents all floors, including the ground floor. Attention has to be paid to additional attic space. Attic space should only be counted if the housing area is more than 50% of the ground floor area. An important field is the building height. Building height is defined as the height from the top edge of the sidewalk to the beginning of the cornice. It has been proven to be the easiest way, if one can measure the distance with a laser – telemeter. If the building height is being approximated this has to be noted. If the building height cannot be measured directly one can also use the measuring tape, put it to the wall of the building and take a photo. The building height can then be determined afterwards. The same procedure can also be done with balconies, etc. If there are shops or cafes at the ground floor, this has to be noted here. Most of the time, if there is a shop at the ground floor this floor represents a soft story. A soft story is a floor (does not have to be the ground floor) where most of the interior walls are missing due to the space needed. Additional attic space can often be determined by looking at the windows at the attic or due to the existence of balconies.

**Fig. 3.7 Steps e and f**

h) Identifying façade elements inclusively number of windows and doors.

The first priority is to determine the number of windows and doors at the facade facing the street. If it is possible to determine the numbers also for the sides facing the courtyard, one should do that. Identifying the façade elements means to determine how detailed the façade design is. Examples are given in the figures below.

**Fig. 3.8 Identifying soft stories and additional attic spaces**
Fig. 3.9 Identifying facade elements

i) Determining non-structural members.

The first thing to determine is the number of chimneys. This is not always easy, because it is possible that one cannot see the chimney from the ground. If it is not possible to count the chimneys this field should be left open.

Fig. 3.10 Example for a building with 7 chimneys

The second thing is to determine all those façade elements that can fall off the building and on the street. This includes sculptures, balconies, statues, etc. It is important to count all
potentially hazardous elements on the façade, so even shop signs have to be considered here.

j) Determining the overall condition of the building.
This part focuses on the overall condition of the building. The main attributes are the presence of water leakage, damages to the roof and cracks in the walls. This mainly means the cracks in the walls. It should, if possible, be distinguished between cracks on the facade (they should not be counted) and cracks in the walls. If the crack is going diagonal it should be counted anyways.

Humidity and Efflorescence can often be seen by different colours on the facade.
Damages at the roof can often be determined if one can see signs of humidity on the facade. If it is possible to get into the building, one should make photos and document it well. Damages at the roof can be very dangerous if not properly treated.

k) Noting irregularities/anomalies.

If there is anything out of the ordinary that is not explicitly in the checklist this is the place to write it down. If anything is written down here, it should always be documented with a photo if possible.

l) Taking pictures with the digital camera.

A software program can modify pictures and combine them. The software is designed to reconstruct a coherent building out of your photographs. Note that since it is an automatic process, it can always lead to unexpected results. In order to avoid these degenerated cases, please take your photos with care and follow those guidelines. For each new reconstruction project you should focus on only one building, or even only one facade.

Having chosen your facade, plan the track, how could you walk and take the photos. You should move in approximately a half-circle around the facade. Note, those coherent paths, with distance of about 1-3 steps between the shots deliver best results.
In order to obtain a coherent point-cloud of your object, you should try to keep as much as possible of the object (facade) in each photograph.

It might not always be possible to move to good locations: e.g., due to obstacles in front of you or due to other buildings, cars or other objects in the near. In such cases try to move around them, even if you have to interrupt your path, but again try to keep as much as possible of the facade in each picture. Do not supply ambiguous content. Note, that the algorithm matches the photos by their visible properties. Do not deliver images which you couldn't distinguish by yourself. For example, if you want to reconstruct highly repetitive facade, it will confuse the software and produce mismatches. In general it is better to supply fewer images with good quality, than too many poor photos.
Fig. 3.17 Always try to keep the whole facade in the view port of your camera.

Fig. 3.18 Facade with highly repetitive content. If you make close-up photographs from two ends of such building, they will be ambiguous. This is the type of input to be avoided.

Fig. 3.19 Unclear data: difficulties in distinguishing among the sides of the building.
Building Identification Process – an example

This section provides an example for the building identification process. The following example describes a part of the process for the city of Vienna. The first thing to do is choosing an area of interest and collecting all information about the area that does not need field work: street plans, building plans, geology maps, etc. Once this information has been gathered the route of the screeners can be identified. If the buildings to be identified are selected, the screeners can begin to investigate the area. It has been shown that the best way to begin the process is to have a very detailed route and detailed plans for the field observations. The last step is transferring the information on the BIP Data Protocols into the relational electronic Building BIP Database. This requires that all photos are numbered (for reference purposes), and that additional fields (and tables) be added to the database for those attributes not originally included in the database. After arriving at the site the screeners observe the building as a whole and begin the process of gathering the information in the building identification protocol, starting with name, date, time, protocol number and the street address. The next step is to take photos of the building. This step can also be performed at the end of the screening process, after filling all the fields of the protocol. After determining the building usage, the construction year and the construction type are being determined. These two fields can also be left empty, in case that the construction year or type cannot be determined for sure. The next big block of fields is pretty easy to determine, number of persons/dwelling units, ground plan, elevation and façade. Non-structural members cannot always be determined properly like number of chimneys. The procedure is the same as for the construction year, if the number cannot be determined for sure, the field should be left empty. After determining the overall condition of the building there is a big field for irregularities. In each example there is an oriel starting at the first floor. This is written in this field and a photo is taken.
Application and validation study in the city of Vienna

**Fig. 3.20 Building Identification protocol**

<table>
<thead>
<tr>
<th>Protocol for building identification procedure</th>
<th>Name: Vukovic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date: 29.04.2010</td>
<td>No. 22</td>
</tr>
<tr>
<td>Time: 12:45</td>
<td></td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Address:</th>
<th>Sheet / No.</th>
<th>Jägerstraße</th>
<th>42</th>
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<tbody>
<tr>
<td>PLZ</td>
<td></td>
<td>1201</td>
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<table>
<thead>
<tr>
<th>Photo number: from: 3886 to: 3525</th>
<th>01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Usage: Residential/Commercial (1995)</td>
<td>02</td>
</tr>
<tr>
<td>Construction Year: 2003</td>
<td>03</td>
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</table>

<table>
<thead>
<tr>
<th>Construction Type</th>
<th>Masonry</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reinforced Concrete</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel Frame</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Persons/Dwelling Units</th>
<th>Number of Dwelling Units</th>
<th>22</th>
<th>05</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of Persons Working</td>
<td>10</td>
<td>06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ground Plan</th>
<th>Corner Building</th>
<th>X</th>
<th>07</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adjacent Buildings right</td>
<td>X</td>
<td>08</td>
</tr>
<tr>
<td></td>
<td>Adjacent Buildings left</td>
<td>X</td>
<td>09</td>
</tr>
<tr>
<td></td>
<td>Rectangular Ground Plan</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Distance to Traffic Area</td>
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<td>11</td>
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</table>

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Number of Floors (inclusive Ground Floor)</th>
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<th>12</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Building Height</td>
<td>25.5 m</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Shops at the Ground Floor</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Attic Space added</td>
<td>X</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Soft Story</td>
<td>X</td>
<td>14</td>
</tr>
</tbody>
</table>

| Facade                | Number of Windows and Doors | 67 | 16 |
|-----------------------| Facade Design | non | 17 |
|                       | simple |   |    |
|                       | detailed | X |    |

<table>
<thead>
<tr>
<th>Non-Structural Members</th>
<th>Chimneys</th>
<th>none &lt; 3</th>
<th>3 &gt; 5</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Detailed Facade Elements</td>
<td>none &lt; 3</td>
<td>X</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Sculptures/Statues</td>
<td>X</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>none &lt; 3</td>
<td>3 &gt; 6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Condition</th>
<th>Cracks</th>
<th>X</th>
<th></th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Humidity/Efflorescence</td>
<td>X</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Damage on the Roof</td>
<td>X</td>
<td></td>
<td>23</td>
</tr>
</tbody>
</table>

| Anomalies Irregularities | From the first floor up there is an one | | | | 24 |

---

70
Fig. 3.21 Building photos taken of a single building with two street views
3.2.3 Input data in EQvis

Building Data
The protocols of the last chapter had to be ingested into the software platform. First, the data was put into shapefiles, which were created prior to the survey. Each building point gets an attribute table where the data of the survey is stored. The next step is to ingest the data in the platform. The following figures show the data in the platform which then serves as the basis for all analyses performed within the project.

![Fig. 3.22 Buildings in the test area together with a small example of the attribute table](image)

Railway Data

![Fig. 3.23 Railway tunnels (left) and bridges (right) in the test area](image)
Road Network Data

Fig. 3.24 The road network (left) and road bridges (right) in the test area

3.3 EQVIS DETERMINISTIC ANALYSIS: OUTPUT DATA

3.3.1 Seismic hazard

Fig. 3.25 PGA distribution for the “method testing” earthquake in EQvis (left); PGA distribution for the “Neulengbach” earthquake in EQvis (right)

EQvis produces the hazard in a deterministic way. For the case study in Vienna two different earthquakes are considered. A historical earthquake from 1590 located in Neulengbach with a magnitude of 6 and a “method testing” earthquake with a magnitude of 7. Table 3.1 gives the characteristics of the earthquakes produced for the simulations. In Fig. 3.25 one can see
a screenshot of the PGA distribution around the test area. The attenuation functions used were the Campbell and Borzogia (2006) NGA functions.

Table 3.1 Earthquakes created for the simulations

<table>
<thead>
<tr>
<th></th>
<th>Neulengbach</th>
<th>method testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnitude</td>
<td>6.00</td>
<td>7.00</td>
</tr>
<tr>
<td>longitude</td>
<td>15.909722</td>
<td>16.543582</td>
</tr>
<tr>
<td>latitude</td>
<td>48.200278</td>
<td>48.0366424</td>
</tr>
</tbody>
</table>

The soil types are also considered. The soilmap of the test area is shown in Fig. 3.26.

3.3.2 Results

As mentioned in the previous sections two earthquakes have been created and analyses have been performed with the results. The two earthquakes are a little bit different, since the Neulengbach earthquake is much further away from the test area with a lower magnitude than the “method testing” one.

Since the PGA values in the test area are different, the damages to the various structures and systems are different. It was decided to display the damages in two different ways for the two earthquakes. The damages caused by the Neulengbach earthquake will be shown as the probability of reaching the damages state “slight”, which is the first damage state in the fragility curves used.

In the case of the “method testing” earthquake a different formula for deriving a “mean damage” will be used. The formula for calculating the mean damage is

\[
\text{meandamage} = g_i + g_m m + g_h h + g_c c
\]

(3.1)

where \(i\) is the probability of reaching the damage state “slight”, \(m\) is the probability of reaching the damage state “Moderate”, \(h\) is the probability of reaching the damage state \(\ldots\)
“Heavy” and \( c \) is the probability of reaching the damage state “Complete”. The factors before the probabilities are called “damage ratios” and can be specified by the user when ingested. The damage ratios used in this test case are written in the following table.

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<thead>
<tr>
<th></th>
<th>Insignificant</th>
<th>Moderate</th>
<th>Heavy</th>
<th>Complete</th>
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<tr>
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<td>1</td>
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<td>railway tunnel</td>
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<td>0,08</td>
<td>0,25</td>
<td>1</td>
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</tbody>
</table>

### Results for the “method testing” earthquake

The first and most important result is the damage to the building stock where the results are obtained building by building. The user can quickly look at the results for each building and filter them. Each building has a very detailed description of the contents as described in the previous chapters.

The distribution of damage to the buildings shows that the building stock is very homogenous. There are very few building collapses, some heavily damaged buildings but the majority of the building stock remains in good condition.

The damage to the railway tunnels is very low compared to the building damage. There is only one tunnel with a mean damage of 0.05 which is very low. It was expected that an earthquake of this magnitude and distance will not produce major damages to tunnels in general.
The maximum mean damage to railway bridges is 0.11 which is not that small anymore. As expected the bridges closer to the epicentre as well as the bridges with poor soil conditions have the highest values.

The damage to road bridges is similar to the damages to the railway bridges. As before, the mean damage increases towards southeast. The damage to the road network is quite large. The maximum mean damage is around 0.12.

**Results for the “Neulengbach” earthquake**

This case is very interesting since this is a real earthquake that happened in 1590. There are very few articles and data about the consequences of this earthquake, but there were reported some damages to some buildings in Vienna. The simulation also shows some
potential of failure of some buildings. The maximum mean damage is around 0.14 with moderate damage probabilities up to 0.34.

Fig. 3.30 Building damage for the “Neulengbach” earthquake

The damages to roads, road bridges, railway bridges and tunnels are very low. All the figures show the probability of reaching the damage state “slight” and the maximum value is 0.18. There were no reports of damages to these systems in the archive of the earthquake, so it is not expected that there was damage back in 1590.

Fig. 3.31 Railway tunnel (left) and bridge (right) damage for the “Neulengbach” earthquake
3.4 OOFIMS PROBABILISTIC ANALYSIS: INPUT DATA

The input for the OOFIMS runner has been provided in an Excel file that contains all the relevant information of hazard, buildings, water supply system, road and electric power network. The probabilistic analysis used the Monte Carlo method, selecting a minimum value for the covariance of 0.02 and performing 10000 runs. Each run is characterized by a different location and intensity of the earthquake, producing consequently different scenario of damage (Campbell and Bozorgnia 2006).

3.4.1 Seismic hazard

Fig. 3.33 shows the seismic zones that could affect the Vienna site. The input is given in the Excel file of Fig. 3.34, providing for each subzone the coordinates of the polygon and the seismic specifics as the fault rake and the fault mechanism.

Akkar and Bommer (2010) ground motion prediction equation has been used, choosing the peak ground acceleration as primary Intensity Measure and area fault as source model.
Expected values of magnitude can vary in the interval 4.8 - 6.2, according to the historical seismicity of the zone.

<table>
<thead>
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<th>grid description</th>
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<th>landable susceptibility map name</th>
<th>Vs30 map name</th>
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</table>

**Fig. 3.34 Input of the seismic hazard**

3.4.2 Buildings

Brigittenau district has been divided into two land use zones, one in the north and one in the south (Fig. 3.35). 3 main sub-city districts are also identified (Fig. 3.36): for each of them, general information concerning the buildings and their inhabitants (as respectively average building height and employment rate) are given as input.

In addition, 11 census tracts have also been identified (Fig. 3.36). While in the deterministic analysis performed with EQvis, buildings have been input one by one, each one with its own characteristics, in OOFIMS probabilistic analysis, the buildings have been grouped into zones (census tracts) and for each of those zones, the structural features of the buildings have been statistically classified.

**Fig. 3.35 Brigittenau district and the land use plan (right)**
Then, for each typology of buildings, the more appropriate fragility curve has been selected (Table 3.3). The final input, (Fig. 3.37), gives for each census tract the percentage of buildings associated to the fragility curve selected.

### Table 3.3 Fragility curves used in Vienna test case for RC and masonry buildings

<table>
<thead>
<tr>
<th>Fragility curves</th>
<th>IMT</th>
<th>RC buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borzi et al. 2007-RC - 8 storeys-seismicallydesigned (c = 10 %)</td>
<td>PGA</td>
<td></td>
</tr>
<tr>
<td>Borzi et al. 2007-RC - 4 storeys-seismicallydesigned (c = 10 %)</td>
<td>PGA</td>
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<tr>
<td>Erberik 2008 - RC - low rise bare frame LRBR</td>
<td>PGV</td>
<td></td>
</tr>
<tr>
<td>Erberik 2008 - RC - mid-rise bare frame MRBR</td>
<td>PGV</td>
<td></td>
</tr>
<tr>
<td>Erberik 2008 - RC - mid-rise infilled frame MRIR</td>
<td>PGV</td>
<td></td>
</tr>
<tr>
<td>Erberik and Elnashai 2004 – RC flat slab - mid-rise infilled frame MRINF</td>
<td>Sd</td>
<td></td>
</tr>
<tr>
<td>Kappos et al. 2003 - RC3.1-HR-HC</td>
<td>PGA</td>
<td></td>
</tr>
<tr>
<td>RISK-UE 2003 - RC moment frame-HR-HC-UTCB hybrid approach</td>
<td>Sd</td>
<td></td>
</tr>
<tr>
<td>RISK-UE 2003 - RC moment frame - LR-HC-UTCB hybrid approach</td>
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<tr>
<td>RISK-UE 2003 - RC moment frame - MR-HC-IZIIS approach</td>
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<td></td>
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<tr>
<td>Vargas et al. 2010 - RC - 8 storeys</td>
<td>Sd</td>
<td></td>
</tr>
</tbody>
</table>

| Masonry buildings |
|-------------------|-----|
| Borzi et al. 2008b - MA Brick - High percentage voids - 2 storeys | PGA |
| LESSLOSS 2005-adobe and rubble stone - 8-15 storeys - Lisbon | Sd |
| RISK-UE 2003 - M12-HR-UNIGE approach | Sd |
| Borzi et al. 2008b - MA brick-low percentage voids - 4storeys | PGA |
| RISK-UE 2003 - M12-LR-UNIGE approach | Sd |
From the statistical analysis, it results that 70% of the buildings in the district are masonry buildings, the remaining 30% are reinforced concrete ones. All the sub-districts have a preponderance of masonry buildings; only in the 5th sub-districts the percentage of reinforced concrete buildings is greater than the one of masonry buildings (Fig. 3.38).

3.4.3 Road network

Fig. 3.39 represents the road network (RDN) in Brigittenau district. Two main roads cut the district in the north-south direction (Jägerstraße and Brigittenauer Lände in the western side, along the Donau Kanal). Wallensteinstraße links the east side (where also a freight harbor is) to the west side of the city through the Friedensbrücke over the Donau Kanal.

Each node of the RN is defined by its longitude & latitude; each side by its starting and ending nodes (Fig. 3.40). From a functional point of view, starting and ending nodes on the north-south and east-west directions are defined as external nodes; the nodes where the main roads intersect are CBD-TAZ (Central Business District - Traffic Analysis Zones) type nodes; all the other are simple intersection nodes. All nodes are considered as not-vulnerable (Fig. 3.40). Road sides (Fig. 3.40) are divided in principal (around 1000 vehicles per hour) and minor (600 vehicles per hour). Principal roads are classified as major arterials; among the minor roads, we distinguished the primary collectors (those directly linking the major arterials to the smallest roads) and the secondary collectors (the viability of which in case of extensive collapses would not strongly affect the viability of other roads) (Fig. 3.40). The majority of road sides have 2 traffic lanes (roadsegmentA); Brigittenauer Lände has 4 traffic lanes (therefore considered as a roadsegmentB). All the sides are considered as vulnerable.

For each road it is also given its width, the distance with the adjacent buildings, specifying also if there are buildings on both sides or only on one side (Fig. 3.40). The site characterization is expressed in terms of Vs 30 values (at nodes and sides), site class, and yield acceleration.

Neither tunnel, nor bridge is in the part of the district analyzed, therefore only fragility for pavements have been used. In particular, two fragility functions form HAZUS have been used: pavement with 2 lanes and with 4 lanes (NIBS 2004).
### Fig. 3.39 Road Network in Brigittenau

![Road Network in Brigittenau](image)

<table>
<thead>
<tr>
<th>NODE</th>
<th>lat. (°)</th>
<th>lon. (°)</th>
<th>x (m)</th>
<th>Va38 (m/s)</th>
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### Fig. 3.40 Road Network input: nodes and sides

![Road Network input: nodes and sides](image)
3.4.4 Water supply system

Fig. 3.41 represents the Water Supply System (in orange) overlaid to the Road Network (in gray): in most of the cases Water Supply System follows the Road Network (with some exceptions). Three external points (one on the north, one on the west and one on the south-east) represent the constant tank nodes that supply the water to the entire district (Fig. 3.42). No vulnerability is assigned to the nodes, while all sides are considered vulnerable.

Sides that deliver the water from the supply-nodes have bigger pipes diameter (1200 mm); the other sides have smaller diameter (600 mm). Only 2 diameter sizes are present (see top line of Fig. 3.42). All the pipes are in cast iron and lay 2 m under the ground level (Fig. 3.42).

Also here, the site characterization is expressed in terms of Vs 30 values (at nodes and sides), site class, and yield acceleration.

![Fig. 3.41 Water Supply System overlying to the Road Network](image-url)
3.4.5 Electric power network

The Electric Power Network follows the layout of the Water Supply System (Fig. 3.43). Two generator nodes are identified: one on the west side of the district where the thermal waste treatment plant of Spittelau is; the other one on the east side. The network lay underground and has a voltage of 230 kV. Also here, the site characterization is expressed in terms of Vs 30 values (at nodes and sides) and site class Fig. 3.44.

Two set of 10,000 runs have been performed: the first simulation considers interdependency among electric power network and water supply system, the second instead considers the two systems not dependent from the other.
3.5 OOFIMS PROBABILISTIC ANALYSIS: OUTPUT DATA

3.5.1 Average results

In the output of OOFIMS calculation the case study area is subdivided into cells and calculations are performed for each cell. Cell dimension is approximately 100x100 m (Fig. 3.45).
The results reported below refer to the case which interdependency is considered among the water supply system and the electric power network. In particular in what follows we report the data obtained by averaging the results of each run over the total number of runs. This implies that damage level (for buildings, roads, water supply system, and electric power network) spans in the range 0-1, while deaths and injured average (being obtained as sum of affected persons divided by 10000) can have different range.

**Buildings**

Fig. 3.46 and Fig. 3.47 present respectively the damage distribution and the affected persons in the area of interest. Biggest damage level and death/injured persons are mainly concentrated in the south zone of the district where there are almost only masonry buildings.

Analyzing the mean annual frequency of exceedance and the moving average (Fig. 3.48) one can obtain:

*Mean annual frequency of exceedance – deaths - 500 years return period earthquake:*

\[
0.7 \times 10^{-3} \times 35402 \text{ (inhabitants)} = 24 \text{ (dead persons)}
\]

*Moving average – deaths – average over all runs:*

\[
1.1 \times 10^{-4} \times 35402 \text{ (inhabitants)} = 4 \text{ (dead persons)}
\]

This means that for an earthquake with 500 years of return period, expected fatalities are 24 while over 10,000 runs average death persons tends to the value of 4.
Fig. 3.46  Average building collapse (left) and building yielding distribution (right)

Fig. 3.47  Average death (left) and injured (right) distribution
Fig. 3.48 Mean annual frequency of exceedance and moving average (death persons)

From Fig. 3.49:

*Mean annual frequency of exceedance – injured persons - 500 years return period earthquake:*

\[ 1.9 \times 10^{-3} \times 35402 \text{ (inhabitants)} = 67 \text{ (injured persons)} \]

*Moving average – injured persons - average over all runs:*

\[ 3 \times 10^{-4} \times 35402 \text{ (inhabitants)} = 11 \text{ (injured persons)} \]

Fig. 3.49 Mean annual frequency of exceedance and moving average (injured persons)

Expected casualties for a 500 years return period earthquake are around 62 and average injured person is around 10 persons.
Roads

Analysis of the roads damage has shown that blocked as well as unusable ones are concentrated in the proximity of collapsed buildings (Fig. 3.50).

Fig. 3.50  Average blocked roads (left) and unusable ones (right)
**Water supply system**

Pipes and nodes of the water supply system results to be slightly affected from the earthquake and average level of damage is negligible (Fig. 3.51).

![Fig. 3.51 Pipes broken (left) and non-functional nodes (right)](image)

**Electric power network**

Also the electric power network results to be slightly damaged as shown in Fig. 3.52.

![Fig. 3.52 Average damage on the electric power network nodes](image)
3.5.2 Selected scenario

Among the 10,000 runs, a particular scenario has been selected. It presents a 5.4 magnitude earthquake located in the south-east of Vienna, at a distance of approximately 50 km from Brigittenau district (Fig. 3.53). The selected scenario is considered meaningful since it is in the proximity of the tectonic zone of the Austrian region more prone to seismicity.

This scenario produces a PGA distribution as in Fig. 3.54. For the sake of simplicity, the values refer to hard rock, realistic ones should account of soil typology in each point of the calculation.

![Map showing the location of the 5.4 magnitude earthquake](image1.png)

**Fig. 3.53** M = 5.4 earthquake 50 km far from Brigittenau district, south-east of Vienna

![PGA distribution on rock](image2.png)

**Fig. 3.54** PGA on rock for the selected event of M = 5.4
Buildings

Fig. 3.55 and Fig. 3.56 present respectively the distribution of collapsed and yield buildings, death and injured persons and displaced persons in case of good and bad weather conditions. Deaths distribution is in accordance with the collapsed buildings. Major damaged are registered, as in the averaged results, in the south of the district where mainly masonry buildings are present.

Fig. 3.55 Number of buildings collapsed (left) and yield (right) for the selected event of $M = 5.4$

Fig. 3.56 Number of deaths (left) and injured (right) persons for the selected event of $M = 5.4$
Fig. 3.57 shows the distribution of displaced persons: the main difference among the case of bad weather and good weather is that in the first case it increments the number of displaced persons in the north part of the district where reinforced concrete buildings are mainly present.

**Fig. 3.57  Number of displaced persons in case of bad weather (left) and good weather (right)**

**Roads**

**Fig. 3.58  Blocked roads (left) and unusable ones (right) for the selected scenario**
Road damage is presented in Fig. 3.58. It confirms the tendency already identified in the analysis of the average damage with blocked and unusable roads mainly located in the south of the district.

**Water supply system**

Selected scenario does not produce any damage to the water supply system. This is expected considering that the average damage level obtained before was negligible.

**Electric power network**

Finally, Fig. 3.59 presents the damage level that affects the electric power network.

![Fig. 3.59 Damage level on the electric power network for the selected scenario](image)

Table 3.4 reports the summary of damage caused by the selected event.

<table>
<thead>
<tr>
<th>Table 3.4 Data from the selected event</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Selected event:</strong> 278</td>
</tr>
<tr>
<td><strong>M = 5.39</strong></td>
</tr>
<tr>
<td><strong>Hypocenter:</strong> 17.0071, 48.0789 Depth: 10 km</td>
</tr>
<tr>
<td>EPN - Broken Transmission Stations</td>
</tr>
<tr>
<td>EPN - Non functional demands</td>
</tr>
<tr>
<td>WSS - Broken pipe</td>
</tr>
<tr>
<td>WSS - Non functional demands</td>
</tr>
<tr>
<td>RDN - Broken</td>
</tr>
<tr>
<td>RDN - Blocked</td>
</tr>
</tbody>
</table>
3.5.3 Interdependency among water supply system and electric power network

Fig. 3.60 compares the mean annual frequency of exceedance for the weighted connectivity loss of the water supply system in case interdependency with the electric power network is considered or neglected.

![Weighted Connectivity Loss for the water supply system with and without interdependency with the electric power network](image)

It results that for an earthquake with 500 years of return period, the weighted connectivity loss for the water supply system is around 0.23 when interdependency with the electric power network is considered, while it increments to 0.28 when it is neglected.

3.6 CONCLUSIONS

The Vienna test case within the SYNER-G project has brought a proof of concept and taught us a number of interesting lessons. It has been proven that an assessment process building by building is feasible with the concept developed in SYNER -G. It turned out to be sufficient to have untrained personnel performing the large data gathering exercise. This will help to implement it on a very large scale and in any region of the world. IT tools are available to support the data collection and provide help to the involved forces.

The application of the methodology to a limited area with very detailed information provides a challenge for both the software application as well as the data collection. All elements of the SYNER -G development have been applied successfully. Both IT tools, namely the OOFIMS toolbox and the EQvis platform, have been applied. OOFIMS models the systemic interdependencies whereas EQvis is able to allow a user-friendly in and output of results. Visualization plays a major role when stakeholders and officials engaged in civil protection enter the procedures. The EQvis software platform with the integrated OOFIMS toolbox is available as an open-source product for free download at the homepage.

For the proof of concept 2 different earthquake scenarios have been simulated:
• the historic 1590 earthquake of Neulengbach (M= 6.0) which represents a real case where good documentation is available

• a benchmark earthquake of high intensity (M= 7.0) in order to test the reaction of the model to a disastrous earthquake located in the south of the Vienna Basin.

A plausibility check on the results of the three cases has been performed and it has been stated that they match with the expectations of the expert community. The results in terms of buildings are rated excellent whereas the results on the utility networks are limited because of the small area involved, which easily leads to a complete failure of a network due to missing redundancy.

It will be a challenge to enlarge the dataset to the entire city (180,000 buildings instead of 700 in the test area). It will bring new challenges in terms of computing power and number of interrelations to be handled. Furthermore, it is recommended to produce an online data generation sheet to allow filling the database with the necessary information. In order to perform this exercise it will be necessary to establish a large IT project that enlarges the current boundaries of application.
4 Application and validation study in the gas network of L’ Aquila

4.1 INTRODUCTION

Past earthquakes have caused significant amount of damage to gas networks, especially on buried pipelines (O’Rourke and Palmer 1996; FEMA 1992). The 1971 San Fernando earthquake caused extensive damages to underground welded-steel transmission pipelines. The 1923 Kanto earthquakes caused over 4000 breaks to gas pipelines in the Tokyo region. Damage on above ground support facilities such as tanks and compressor stations were also observed in past events (FEMA 1992), especially in the case of inadequate anchorage of equipment that led to rupture of electrical connections.

A gas system as a whole is comprised of: 1) a number of point-like critical facilities (production and gathering facilities, treatment plants, storage facilities, reduction stations where gas is pressurized/depressurized or simply metered); 2) the pipelines constituting the transmission/distribution network; 3) the supervisory control and data acquisition sub-system, namely SCADA.

The most critical component are pipelines because they are buried and consequently subjected to transient ground deformation (TGD), due to seismic wave propagation, and permanent ground deformation (PGD), due to soil instability phenomena such as liquefaction and landslides. Therefore, the causes of physical damages to components of gas systems included large permanent soil deformations produced by fault displacements, landslides, liquefaction of sandy soils and associated lateral spreading and ground settlements, as well as ground strains associated with travelling seismic waves. Ground shaking usually affects wide geographical areas and can produce well-dispersed damage. Damage induced by permanent ground deformation typically occurs in isolated and localized areas and results in high damage and consequent repair rates, varying in relation to the amount, geometry, and spatial extent of the PGD zone. Evidence reported in literature indicates that underground pipelines perform worse in areas experiencing significant permanent displacements.

In this chapter, after a brief introduction presenting the general framework for the seismic risk assessment of a gas network, according to the SYNER-G methodology, the case study of L'Aquila gas distribution system is described, and the process for the seismic performance characterization is summarized. Subsequently, the analysis of the system is carried out at the connectivity level and results in terms of performance indicators are presented and discussed for the different cases that have been considered.

This reference report is strictly related to other SYNER-G products, which the reader should have available for a comprehensive understanding of the application. These are D2.1 (Franchin et al. 2011), D2.4 (Esposito et al. 2011), D2.13 (Weatherhill et al. 2011), D3.4 (Gehl et al. 2011), D5.3 (Esposito and Iervolino 2011b) and D6.5 (Esposito and Iervolino 2012b).
4.2 RISK ASSESSMENT METHODOLOGY AND PROCEDURE

In the following the general framework for the risk assessment of a gas network is briefly presented according to the SYNER-G methodology. Since the application study refers to a gas distribution system, the general methodology is referred to the components of this system, i.e., pipelines and reduction stations.

4.2.1 Systemic vulnerability methodology and performance indicators

Components of a gas distribution system, especially pipelines, are subjected to transient ground deformation, due to seismic wave propagation, and permanent ground deformation, due to soil instability phenomena such as liquefaction and landslides.

Ground motion effects are usually described by peak parameters (e.g., peak ground acceleration, PGA, or peak ground velocity, PGV). Since a gas system generally covers a large area, seismic input characterization is comprised of large vectors of ground motion-intensities (for all sites that describe the region where the system is located) that may be spatially correlated. Furthermore, the performance of spatially distributed systems may be conditional upon the failure of many components each of which is sensitive to different IMs. Therefore seismic input assessment has to take into account the possibility of the existence of a cross-correlation between IMs (Loth and Baker 2011). To address this issue, spatial correlation models and conditional hazard approach may be considered; it consists of obtaining as first step the joint probability density function (PDF) of a primary intensity measure (IM) at all locations by a multivariate distribution characterized by a spatial correlation function (e.g., Esposito and Iervolino 2011a, 2012a) and then a conditional distribution of a secondary IM (e.g., PGV) given the occurrence of a primary IM (e.g., PGA) (Iervolino et al. 2010; Chioccarelli et al. 2012). The second important aspect to consider in seismic input characterization is that the presence of buried components (i.e., pipelines) implies the consideration of permanent ground deformation hazards such as landslides, liquefaction-induced lateral spreading, and seismic settlement (O’Rourke and Liu, 1999).

There are many models available that have the intent to relate the PGD, and the probability of occurrence of each geotechnical hazard, to the strength of ground motion (typically measured in terms of PGA), but the main limiting factor of several of these models is the requirement of very detailed data, which may impair actual applicability for lifelines’ analysis. Therefore, it may be preferable to consider simpler models, as the approach implemented in HAZUS (FEMA 2004), and described in SYNER-G report D2.13 (Weatherhill et al. 2011).

To estimate earthquake damage, given knowledge of ground shaking (or ground failure), earthquake intensity parameters have to be correlated with damage in terms of fragility functions for system components. In fact, these relations provide the probability of reaching or exceeding a particular damage state (level of damage) given the level of ground shaking (or ground failure). To this aim, the typological classification of each component, damage scale definitions, and the intensity measures, have to be defined.

In the case of pipeline components, fragility curves available in literature are usually based on empirical data collected in past earthquakes. The most common practice is to evaluate the repair rate, $R_r$, as the number of pipeline repairs in an area divided by the length of the pipelines in the same area, with respect to a parameter representative of ground shaking or ground failure. A corrective factor $K$ is usually added to the fragility model in order to account different factors that affect the vulnerability of pipelines such as pipe material, pipe diameter.
or pipe connections. For example, considering a linear model, fragility function may be expressed as in Eq. 4.1, where \( a \) is a constant:

\[
R_R = K a IM
\]  

(4.1)

As mentioned before, buried pipelines are sensitive to permanent ground deformation (resulting from various ground failures), in addition to transient ground deformation due to seismic wave propagation. Among the various seismic parameters used to correlate the ground motion effects to the damage suffered by buried pipelines, PGV has been identified as the one having a more direct physical interpretation (O’Rourke et al. 1998). Many PGV fragility relations are available in literature; for a discussion see SYNER-G report D3.4 (Gehl et al. 2011). Regarding ground failure effects, permanent ground deformation (PGD) is used as the demand descriptor.

According to HAZUS (FEMA 2004), two damage states may be considered for pipelines: leaks and breaks, and the type of damage depends on the type of hazard. In particular, when a pipe is damaged due to ground failure, it is assumed that the proportions of leaks and breaks are 0.8 and 0.2, respectively; whereas for ground shaking, leaks and breaks relative proportions are 0.2 and 0.8, respectively.

In the case of stations, three different types may exist in a gas distribution system: (1) metering/pressure reduction stations (M/R stations) that contain metering equipment for monitoring and measuring the gas flow, and reduction lines for the compression of the gas pressure before its distribution into the pipe system; (2) regulator stations, where the gas pressure is reduced as required for the gas to arrive to the end-user; and (3) metering stations that are only flow measurement points.

Although in literature no fragility curves are available for these components, some authors (e.g., Chang and Song 2007; Song and Ok 2009) assume that these facilities (especially metering/pressure reduction stations) can be characterized with the same fragility features of compressor stations. Damage states and fragility curves for compressor stations are usually defined and associated with PGA sometimes PGD, if located in liquefiable or landslide zones (FEMA 2004). Moreover, since these facilities may include many subcomponents, fragility curves are usually obtained aggregating the fragility of each subcomponent through the use of a fault tree analysis.

Further system performance measures are used in order to evaluate the interaction between component response to earthquake and lifeline performance. For the specific case of a gas network, the performance may be measured generally in two ways:

- Connectivity between node pairs (where the main goal is related to determine the probability of the existence of a path connecting the source and the demand node when the links and the nodes are subjected to random failure events), that allows assessment of serviceability in terms of the aggregate functionality of facilities (nodes) composing the system; i.e., the number of distribution nodes which remain accessible from at least one supply node after the earthquake;

- Flow-performance, that includes consideration of the network’s capacity; e.g., maintaining minimum head pressure related to leakages from two particular points of the network or related to a demand node.

Selected references and examples of these two approaches can be found in the SYNER-G report D2.1 (Franchin et al. 2011).
Application and validation study in the gas network of L’Aquila

Starting from the analysis of seismic damage to gas system components a connectivity or flow-based analysis can be carried out in order to evaluate the system performance of the damaged network. Depending on the purpose of the analysis, different methods and tools can be used for the evaluation of seismic performance. For a discussion on the approaches that may be used for the modeling and the analysis of the gas network for the two methods (connectivity and flow-reliability) see SYNER-G report D5.3 (Esposito and Iervolino 2011b).

The quantitative measure of the seismic performance is given by Performance indicators (PIs), that express numerically the impact of the earthquake on the systemic vulnerability, quantifying the degree to which the system is able to meet established specifications following a seismic event. For a gas network two possible PIs that may be used for a connectivity analysis are the Serviceability Ratio (SR) and the Connectivity Loss (CL). The first index, originally defined by Adachi and Ellingwood (2008) for water supply systems, is directly related to the number of distribution nodes in the utility network, which remain accessible from at least one supply facility following the earthquake. It is computed as in Eq. 4.2:

\[
SR = \frac{\sum_{i=1}^{n} (w_i \cdot X_i)}{\sum_{i=1}^{n} w_i}
\]

where SR ranges in the [0, 1] interval, \(w_i\) is a weighting factor assigned to the distribution node \(i\) (e.g., customers related to the demand node or nominal flow of the distribution node), and \(X_i\) represents the functionality of facility \(i\), which is modeled as the outcome of a Bernoulli trial (\(X_i = 1\) if facility is accessible from at least one supply facility and zero otherwise), and \(n\) is the number of distribution nodes.

The second index, originally defined by Poljanšek et al. (2011), was adapted for the purpose of this study and it is expressed in Eq. 4.3. CL measures the average reduction in the ability of demand nodes to receive flow from sources counting the number of the demand nodes connected to the \(i\)-th source in the original (undamaged) network \(N^i_{\text{demand, orig}}\) and then in the damaged network \(N^i_{\text{demand, dam}}\) where \(\langle \rangle\) denotes averaging over all sources nodes. Further details can be found in the SYNER-G Deliverable 2.4.

\[
CL = 1 - \left\langle \frac{N^i_{\text{demand, dam}}}{N^i_{\text{demand, orig}}} \right\rangle
\]

4.2.2 Software implementation

For the modeling of physical behavior of the network with respect to the general methodology presented in the SYNER-G report D2.1 (Franchin et al. 2011) the object-oriented paradigm (OOP) was adopted. Within such a paradigm the problem is described as a set of objects, “software containers” grouping together related procedures and data. Data elements are called attributes of an object. Procedures which operate on data specific for an object are called methods. Objects are instances (concrete realizations) of classes (abstract models) that are used to model the system.

The SYNER-G prototype software includes an object-oriented representation of several systems, one of which is the gas distribution networks. In particular for the purpose of the
application study the program was equipped with the GAS class, focusing on the components of a gas distribution system, in order to evaluate seismic performance of the case study (L'Aquila gas distribution network).

The gas distribution system class is modeled as an undirected graph and it is considered a subclass of the Undirected abstract class. As shown by the class diagram in Fig. 4.1, the network is comprised of nodes and link/edges. As consequences it is the composition of GASedge and GASnode abstract classes, of which the first is the generalization of PipeGAS class, while the second is the generalization of GASdemand, GASsource and Joint classes.

The Joint class represents all nodes used to reproduce the geometry of the system. The GASsource class is represented by M/R stations that are used to connect the distribution medium-pressure network to the high-pressure transmission lines and the GASdemand is the generalization of IDU class and Station class. The IDU class represents the node directly connected with customers in the low-pressure network while the Station class is represented by RGs that are considered final nodes when the only medium-pressure network is analyzed.

Each class is characterized by attributes and methods. Attributes refer to properties that describe the whole system and each component. For example, for the gas distribution system class, possible attributes may be related to the number of links and nodes presented in the system, the list of sites where vulnerable elements are located, and the corresponding intensity measures, or the connectivity and adjacency matrix used for the evaluation state by

Fig. 4.1 Class diagram for the gas distribution network
state of connectivity-based performance measures. Possible attributes for link and nodes, instead, may be related to geographical coordinates, site class, material and other data necessary as input to compute fragility and component performance measures. Methods refer to functions used to evaluate the state of the network or of each component of the system. For example, possible methods are functions to evaluate the flow in pipes and nodes, or accessibility of demand nodes, or the damage state of links and nodes (if they are considered vulnerable).

A detailed description of properties and methods implemented for the case study is available in the SYNER-G report D6.5 (Esposito and Iervolino 2012b).

4.3 THE CASE STUDY

4.3.1 General description

In Italy the gas supply transmission and distribution systems include the following principal components: (1) high-pressure transmission lines (national scale); (2) M/R stations; (3) medium-pressure distribution networks (regional scale); (4) Reduction Groups; (5) low-pressure distribution networks (local scale); (6) demand nodes; (7) gas meters.

In L’Aquila region the connection of the distribution medium-pressure network to the national high-pressure transmission lines is operated via three metering/pressure regulator stations (Re.Mi. “stazioni di Regolazione e Misura”, in Italian). The three M/R stations of the L’Aquila distribution system are housed in one-story reinforced concrete structures with steel roofs, hosting internal regulators and mechanical equipment (heat exchangers, boilers and bowls) where the gas undergoes the following processes: (1) gas preheating; (2) gas-pressure reduction and regulation; (3) gas odorizing; (5) gas-pressure measurement. The gas is distributed via a 621 km pipeline network: 234 km of which operating at medium pressure (2.5 – 3 bar), and the remaining 387 km with gas flowing at low pressure (0.025 bar – 0.035 bar). The pipelines of the medium and low pressure distribution networks are either made of steel or High Density Polyethylene (HDPE). HDPE pipes have nominal diameters ranging from 32 to 400 mm, whereas diameter of steel pipes is usually between 25 and 300 mm. Steel pipes use gas welded joints, while HDPE pipes use fusion joints. The transformation of the medium distribution pressure into the low distribution pressure is operated via 300 reduction groups (RGs) that are either buried, sheltered in a metallic kiosk or housed within/close to a building. Several demand nodes (IDU, “Impianto di Derivazione Utenza” in Italian), consisting of buried and not buried pipes and accessory elements, to allow the supply of natural gas to utilities, from low pressure network. For large users (e.g., industrial facilities) the demand node IDU is located along the medium-pressure distribution network. It is worth noting that all the components contained in both the L’Aquila M/R stations and RGs are unrestrained and therefore vulnerable to seismic (inertia) forces, as it usually happens for non-structural elements not properly seismically designed.

For the evaluation of seismic performance within this study, the medium-pressure portion of the L’Aquila gas system was selected. In particular, the selected part (shown in Fig. 4.2) is characterized by 3 M/R stations, 209 RGs, and pipelines at medium pressure, either made of steel or HDPE.

For the implementation of the network into the prototype software, it was decided to reduce the amount of data, without compromising the nature of the study; i.e., application to a real
case. In fact, in order to completely respect the geometry of the network, more than one thousands of joint nodes should have been added into the input file. This would have resulted in large computational demand, rendering hardly feasible to run the analysis with the SYNER-G software.

Therefore a data reduction process was employed considering:

- Removal of all final links; i.e., pipes that are not carrying gas to regulators;
- Simplification of the geometry merging pipes with the same geometrical and material properties;

The resulting network is comprised of 602 nodes (3 sources, 209 RGs and 390 joints) and 608 links. All data necessary for the evaluation of seismic vulnerability were imported in the simulation software.
A connectivity analysis was performed within this study. Considering that the function of a gas network at medium pressure is to deliver gas to reduction stations/groups, the network’s performance was assessed evaluating the aggregate availability of end nodes (RGs) composing the L’Aquila gas system.

Both TGD and PGD hazards were evaluated in particular focusing on the effects induced by landslide. Pipes and M/R stations were considered the only vulnerable elements within the network, and risk assessment was performed in terms of two connectivity-based performance indicators for the system.

In the following a detailed description of the application of the SYNER-G methodology to the case study is provided, and results of the analysis are discussed.

### 4.3.2 Seismic hazard

Probabilistic hazard scenarios were simulated for the region covering the case-study network. The process is essentially divided into five separate stages:

1. Simulation of the event on the source;
2. Simulation of the random field of the primary IM (PGA) on rock;
3. Amplification due to local site conditions;
4. Conditional simulation of the cross-correlated ground motion for secondary IMs;
5. PGD estimation.

The Paganica fault (normal fault type) was used as source for the generation of characteristic earthquakes of moment magnitude Mw 6.3 and occurrence rate $\nu = 1/750$ (Pace et al. 2006). Data on geometric source model used herein can be found in Chioccarelli and Iervolino (2010).

The strong ground motion for the primary IM was evaluated using a ground motion prediction equation (GMPE) on a regular grid covering the gas network. The regular grid that covers the region of interest was identified based on the correlation structure of the primary IM; i.e., a grid adequately denser than the IM correlation length (i.e., the range). In this case a grid size of 1 km was chosen. As described in the SYNER-G Deliverable 2.13, the primary IM is chosen as an intensity measure for which a spatial correlation model is available, and it is used to generate a Gaussian Random Field (GRF) and to obtain the secondary IM for each site of interest through the conditional approach. For this case study PGA was identified as primary IM and, since gas network components (pipelines and stations) are also sensitive to PGV (i.e., some of the employed fragility models are expressed in terms of this parameter), the latter was selected as a secondary IM. The GMPE used for the evaluation of strong motion is that by Akkar and Bommer (2010) and spatial variability was modeled using correlation models provided by Esposito and Iervolino (2011a).

For each site of the grid the averages of primary IM from the specified GMPE were calculated, and the residual sampled from a random filed of spatially correlated Gaussian variables according to the spatial correlation model. The value of the primary IM at each site of the network (i.e., the vulnerable elements’ sites) was then obtained interpolating the grid values. The resulting ground motions correspond to rock sites. Then for each site the secondary IM (PGV) was determined by sampling a vector of Gaussian variables described by the conditional mean and variance depending on the primary IM (Iervolino et al. 2010). To
this aim, assuming the joint normality between the two IMs, the correlation coefficient between PGA and PGV was estimated starting from the dataset used for the Akkar and Bommer (2010) GMPE.

Regarding geotechnical hazards (i.e., PGD), the landslide potential of L'Aquila region, according to the HAZUS (FEMA 2004) procedure was performed. Therefore, a susceptibility map of L'Aquila region, based on the lithological group, slope angle, and ground-water condition was obtained. More than forty different outcropping formations were detected in the region of interest starting from 1:50,000 scale ISPRA geological maps (http://www.isprambiente.gov.it). In order to apply the HAZUS methodology the Quaternary deposits and the Meso-Cenozoic formations beneath were grouped into three main subsoil classes (i.e., A,B,C) considering both lithological and mechanical properties of the formations (i.e., the effective cohesion $c'$ and the friction angle $\phi'$). The classification is synthesized in Table 4.1, with the description of each class and the associated values of strength parameters, as suggested by HAZUS. More details on the procedure for the geological classification of the region of interest may be found in the SYNER-G report D6.5 (Esposito and Iervolino 2012b).

Slope angle was generated from topographic data, and was grouped into six slope classes: 3-10, 10-15, 15-20, 20-30, 30-40, >40 degrees. In particular starting from a topographic map 1:25000 (IGM, http://www.igmi.org/prodotti/cartografia/carte_topografiche) a digital elevation model (DEM) of the studied area was obtained with a grid resolution of 40x40m and a height resolution of 7m. The DEM in turn, allowed to obtain the slope angle map, showing that in the city center the gas network is mainly located in flat areas, whereas in the surrounding small villages the network crosses very steep slopes. Extreme groundwater conditions were assumed, by considering either dry (groundwater below the depth of the sliding surface) or wet conditions (groundwater level at ground surface). Since very limited information were available about groundwater table, a dry state was attributed to the outcropping rock while wet conditions were assigned to B and C soil classes.

Therefore, a susceptibility map of L'Aquila region, based on the lithological group, slope angle, and ground-water condition was obtained, and starting from the susceptibility categories a critical acceleration map was derived. In particular, a critical acceleration, $K_c$, value ranging from 0.05g (most susceptible) to 0.6g (less susceptible) was associated to each landsliding-susceptible category. The probability of landsliding was then determined for each site using the susceptibility class and the PGA on free field. If simulated surface (amplified) PGA exceeds the determined value of critical acceleration, then displacement occurs at the site. In this case, PGD is calculated via the Saygili and Rathje (2008) empirical model.

To account for local site conditions GMPE-based amplification factors were considered. To this aim each site of the network was characterized according to the site classification scheme adopted by the Akkar and Bommer (2010) GMPE, starting from geology classification derived for the landslide potential described before.
Table 4.1 Geological groups description for L’Aquila region

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Strength parameters</th>
<th>Local Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Rock</td>
<td>$c' = 15 \text{kPa}$ $\varphi' = 35^\circ$</td>
<td>Limestones - Flysch-Debris</td>
</tr>
<tr>
<td>B</td>
<td>Soft Rock</td>
<td>$c' = 0$            $\varphi' = 35^\circ$</td>
<td>Pleistocene gravels and sands</td>
</tr>
<tr>
<td>C</td>
<td>Clay and Silty Soils</td>
<td>$c' = 0$            $\varphi' = 20^\circ$</td>
<td>Holocene silts and sands</td>
</tr>
</tbody>
</table>

4.3.3 System vulnerability and performance assessment

To estimate earthquake-induced damage, IMs were related to system component damage via fragility models. For buried pipelines ALA (2001) Poisson repair rate function of PGV and PGD, were selected for each pipe typology (steel and HDPE) and diameter, according to analysis of damage occurred on the gas network following the 6 April 2009 L’Aquila earthquake (Esposito 2011).

These relations are expressed in Eqs. 4.4 and 4.5 where $K_1$ and $K_2$ represent the modification factors according to pipe material and diameter.

\[
R_R = K_1 \cdot 0.002416 \cdot PGV \quad (4.4)
\]

\[
R_R = K_2 \cdot 11.223 \cdot PGD^{0.319} \quad (4.5)
\]

where $R_R$ is expressed in $1/\text{km}$ and $PGV$ and $PGD$ are given in $\text{cm/s}$ and $\text{m}$ respectively.

Table 4.2 Parameters for the fragility characterization

<table>
<thead>
<tr>
<th>Component</th>
<th>Author</th>
<th>Damage state</th>
<th>Fragility relation parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TGD</td>
</tr>
<tr>
<td>Steel pipelines (small diameter)</td>
<td>ALA (2001)</td>
<td>Break</td>
<td>$K_1 = 0.6$</td>
</tr>
<tr>
<td>HDPE pipelines (small diameter)</td>
<td>ALA (2001)</td>
<td>Break</td>
<td>$K_1 = 0.5$</td>
</tr>
<tr>
<td>M/R station (Un-anchored)</td>
<td>HAZUS (FEMA, 2004)</td>
<td>Extensive</td>
<td>$\mu(\text{g}) = 0.77$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\mu(\text{inch}) = \text{N/A}$</td>
</tr>
</tbody>
</table>

Regulator groups were not considered seismically vulnerable, mainly because no quantitative fragility curves are available in literature. For the M/R stations, instead, a

1 Note that the M/R station is not vulnerable to PGD because the site where the station is located is not susceptible to landslide according to geotechnical analysis.
lognormal fragility curve for un-anchored compressor stations (FEMA 2004) was adopted. The fragility functions of M/R station and pipelines (steel and HDPE) are summarized in Table 4.2 where log(\(\mu\)) and \(\beta\) are the mean and the standard deviation of the normal distribution function used for the fragility assessment of the M/R station.

Damage states considered for the evaluation of seismic vulnerability are strictly related to the objective of the analysis. In this case a connectivity analysis was performed; i.e., the system is considered functional if demand nodes (regulator groups) continue to provide gas, and then if they remain accessible from at least one supply node (M/R station). To this aim it was assumed that a pipe segment cannot deliver gas when the segment has at least one break, while for the supply node it was assumed that it loses its connectivity when it is in extensive damage state.

As mentioned before, the quantitative measure of the functionality of the gas network is given by performance indicators that are able to quantify the degree to which the system is able to meet established specifications and/or customer requirements following an earthquake event. Herein the Serviceability Ratio (SR), expressed in Equation 4.2 and the Connectivity Loss (CL) expressed in Equation 4.3 were considered. In particular for SR the weighting factor considered is represented by the nominal flow (m\(^3\)/h) of the demand node; i.e., RG.

### 4.4 RESULTS

A Monte Carlo Simulation (MCS) was carried out in order to evaluate the probability of exceeding a predefined level \(u\) of performance, given the occurrence of an earthquake on the fault. This probability was computed empirically using the MCS approach as follows:

\[
\hat{P}(PI > u) = \frac{1}{n} \sum_{j=1}^{n} I(pi_j > u)
\]

Where \(pi_j\) is the performance indicator level corresponding to the simulation \(j\), \(n\) is the total number of simulations and \(I(pi_j > u)\) is an indicator function which equals 1 if \(pi_j > u\) and 0 otherwise. The number of runs of the simulation was defined in order to yield stable estimates of the probability of exceeding the considered PI.

Results indicate that the expected value of connectivity loss given the occurrence of an earthquake is 0.65, i.e., it is expected that the average reduction in the ability of demand nodes to be connected to M/R stations is of 65%. While for the SR indicator, it is expected that 68% of demand nodes receive gas accounting for the importance level related to the nominal flow of the demand nodes. Fig. 4.3 shows the probability of exceedance (complementary cumulative distribution function, ccdf) of the two PIs expressed in Equation 4.6.

In order to evaluate the contribution of some components of the risk on the performance of the network, some variables computed during each run of the simulation were stored and analyzed. In particular regarding hazard, the percentage of sites vulnerable to PGD (i.e., the ratio between the number of pipes where a PGD greater than 0 was occurred and the number of pipes located on sites potentially subjected to landslide) were saved, while in
order to study the effects of the performance state of the components of the network, the number of broken pipes\(^2\) and damaged M/R stations were analyzed. In the following figures (Fig. 4.4, 4.5, and 4.6) histograms and scatter plots of these variables with respect to the two performance indicators are shown.

![CCDF plots for CL and SR](image)

**Fig. 4.3 CCDF and confidence bounds for CL (top) and SR (bottom)**

Correlation coefficients between these variables and performance indicators were also computed in order to evaluate possible linear dependences. As shown in the previous figures it seems that the number of damaged M/R stations is better correlated with the two PIs.

\(^2\) Note that pipes do not share the same length.
Fig. 4.4 Histograms of broken pipes in the simulations (top) and scatter plots of PIs with respect to percentage of broken pipes (bottom)
Fig. 4.5 Histograms of damaged M/R stations in the simulations (top) and scatter plots of PIs with respect to percentage of damaged M/R stations (bottom)
An efficient procedure to investigate the values of variables that contribute most to given values of the network’s performance is disaggregation. Disaggregation of seismic performance, in fact, allows identifying the values of some variables providing the largest causative contribution to the risk given exceedance or occurrence of specified values of the performance indicator. The aim is to evaluate the probability of a variable \( \{X\} \) that is supposed to have an influence on the final performance, conditional to the occurrence of the performance indicator as expressed below:

\[
P[X \mid u_i < PI \leq u_2] = \frac{P[\{X, u_i < PI \leq u_2\}]}{P[u_i < PI \leq u_2]} \tag{4.7}
\]

Therefore, the distribution of the number of broken pipes, damaged M/R stations and the percentage of pipes vulnerable to PGD conditional to the occurrence of the two PIs to ten intervals (equally spaced and ranging from 0 to 1) were computed as in Eq. 4.7 and shown in Fig. 4.7, 4.8 and 4.9.
Fig. 4.7 Relative frequency of the number of broken pipes conditional to CL (top) and SR (bottom)
Fig. 4.8 Relative frequency of the number of damaged M/R stations conditional to CL (top) and SR (bottom)
Fig. 4.9 Relative frequency of percentage of pipes vulnerable to PGD conditional to CL (top) and SR (bottom)
Moreover, for each interval of the two PIs, the bars on the right side of the conditional distribution of the damaged M/R stations taper differently than the bars on the left side; i.e., the conditional distributions are asymmetric. In particular, the distribution of damaged M/R stations conditional to large losses (high values of CL and low values of SR) results skewed to the left, i.e., the mode is in correspondence of an high number of damaged M/R stations while the distribution of damaged sources conditional to high level of serviceability (low values of connectivity loss) results skewed to the right and the mode is in correspondence of a number of damaged M/R stations equal to zero. Regarding other variables, the distributions of number of broken pipes, and percentage of pipes vulnerable to PGD, conditional to the performance of the network are somewhat flat (Fig. 4.7 and 4.9).

Finally, in order to study the effects of regular grid size for the computation of the primary IM, three analyses were set up according to three grid sizes employed: 1 km, 2 km and 5 km. For each grid size an intra-event residual correlation value for PGA was calculated starting from correlation models estimated by Esposito and Iervolino (2011a), i.e., 0.80, 0.64 and 0.33 respectively. These values characterize the correlation of PGA at points located at the extremity of each cell that are assumed instead perfectly correlated. Therefore, the larger is the size of the grid, the larger is the approximation.

Results for the three grid sizes are presented in the following figures. In particular Fig. 4.10 shows the probability of exceedance for the two performance indicators. Although it seems that higher grid sizes tend to underestimate the risk, differences are not so pronounced.

![Fig. 4.10 Exceedance curve of CL (top) and SR (bottom) for the three grid sizes](image-url)
4.5 CONCLUSIONS

This study focused on validating the applicability of the SYNER-G framework on a real case study: L’Aquila (Italy) gas distribution network. The process makes use of probabilistic seismic hazard analysis, empirical relations to estimate pipeline response, fragility curves for the evaluation of facilities’ vulnerability, connectivity performance indicators to characterize the functionality of the network.

The study, in fact, has achieved this goal with special emphasis on the medium-pressure part of the L’Aquila gas system for which detailed information were retrieved. In particular, the selected network was characterized by 3 M/R stations, 209 RGs, and pipelines either made of steel or HDPE. Moreover, for the implementation of the network into the SYNER-G prototype software, it was decided to reduce the amount of data, without compromising the nature of the study. In particular a data reduction process was employed considering: 1) removal of all final links; i.e., pipes that are not carrying gas to regulators; 2) simplification of the geometry by merging pipes with the same geometrical and material properties. The resulting network was comprised of 602 nodes (3 sources, 209 RGs and 390 joints) and 608 links.

In order to characterize the ground shaking hazard of the L’Aquila region, probabilistic scenarios earthquakes were generated using as source the Paganica fault computed for a characteristic earthquake of moment magnitude Mw 6.3. Strong ground motions for the primary IM were evaluated though a European GMPE and a European spatial correlation model on a regular grid covering the gas network. The grid was defined based on the correlation structure of the primary IM; i.e., a grid adequately denser than the IM correlation length. A grid size of 1 km was chosen. PGA was identified as primary IM and, since gas network components (pipelines and stations) are also sensitive to PGV (i.e., some of the employed fragility models are expressed in terms of this parameter), the latter was selected as a secondary IM. The value of the primary IM at each site of the network was obtained interpolating the grid values. The resulting ground motions correspond to rock sites. For each site the secondary IM was determined via conditional hazard.

To account for local site conditions GMPE-based amplification factors were considered. Regarding geotechnical hazards (i.e., PGD), the landslide potential of L’Aquila region, according to the HAZUS procedure was performed. Thanks to a process jointly developed with specialists, the landslide potential in the L’Aquila region was evaluated.

To estimate earthquake-induced damage, IMs were related to component damage via fragility models. For buried pipelines repair rate functions of PGV and PGD were selected for each pipe typology and diameter. Regulator groups were not considered seismically vulnerable, mainly because no quantitative fragility curves are available in literature. For the M/R stations, instead, a lognormal fragility curve for un-anchored compressor stations was adopted.

Damage states considered for the evaluation of seismic vulnerability are strictly related to the objective of the analysis. In this case a connectivity analysis was performed; i.e., the system is considered functional if demand nodes (regulator groups) continue to provide gas, and then if they remain accessible from at least one supply node (M/R station). To this aim it was assumed that a pipe segment cannot deliver gas when the segment has at least one break, while for the supply node it is assumed that it loses its connectivity when it is in extensive damage state.
The adaptation of two connectivity performance indicators (Serviceability Ratio and Connectivity Loss) were considered to include damage of stations and distributing elements into the risk assessment for the system.

A Monte Carlo Simulation was carried out in order to evaluate the probability of exceeding predefined levels of performance, given the occurrence of a characteristic earthquake on the fault.

Results indicate that the expected value of connectivity loss given the occurrence of an earthquake is 0.65. For the SR indicator, it is expected that 68% of demand nodes receive gas accounting for the importance level related to the nominal flow of the demand nodes.

In order to evaluate the conditional contribution of some components of the risk on the performance of the network, disaggregation of performance was performed. The latter refers to: percentage of sites vulnerable to PGD, number of broken pipes, and damaged M/R stations.

Finally, in order to investigate the effect of grid size for the computation of the primary IM, different analyses were set up. In particular three grid sizes were assumed: 1 km, 2 km and 5 km. These were chosen via specific values of correlation of intra-event residuals for the primary IM. The larger is the size of the grid, the larger is the approximation. Results show that coarser discretizations tend, as expected, to (slightly) underestimate the risk.
5 Application and validation study to a transportation network in Italy

5.1 INTRODUCTION

A fundamental distinction among the studies related to the seismic performance of a Road (or transportation) Network (RDN) can be made based on the importance of the role played by the network itself. In a way of simplification, available studies can be assigned to the following three levels:

- Level I: the attention is focused on the functioning of the network in terms of pure connectivity. This type of studies focuses on just one of the services provided by the network, e.g. most typically the rescue function immediately after the earthquake, and may be of interest in identifying portions of the network which are critical with respect to the continued connectivity of the network.

- Level II: the scope of the study is widened to include consideration of the network capacity to accommodate traffic flows. The damage to the network causes traffic congestion, resulting in increased travel time which is in turn translated into monetary terms. This indirect loss summed to direct loss incurred due to damage to the building stock results in a first partial estimate of the overall economic impact of an earthquake.

- Level III: The most general approach, which aims at obtaining a realistic estimate of total loss, inclusive of direct physical damage to the built environment (residential and industrial buildings as well as network components), loss due to reduced activity in the economic sectors (industry, services), and network-related loss (increased travel time). Economic interdependencies are accounted for, such as the reduction in demand and supply of commodities (due to damaged factories, etc.), hence in the demand for travel, and due to the increased travel costs. At this level the relevance and the complexity of the economic models become dominant over that of the transportation network. This is a full systemic study requiring important inputs from the economic disciplines.

The treatment of the third level involves reaching beyond the area of structural engineering and involves important inputs from the economic disciplines. Further, the practical feasibility of these studies requires data, which are seldom available, in terms of both quantity and quality. In particular, studies of the third level necessitate detailed data on the demand and supply of goods and commodities disaggregated by economic sector and spatial location. Collection of this information requires the involvement of governmental bodies.

Two similar examples of Level I studies can be found in Nuti and Vanzi (1998) and in Franchin et al. (2006). In both studies the road network serves the purpose of connecting the hospitals in a regional health-care system. The mortality rate of casualties, in case of seismic event, is substantially reduced if they receive care in a short time. After a strong earthquake, damage and/or congestion of hospitals, and of the transportation network, cause an increase in the distance to be covered, because casualties exceeding the hospitals capacity have to
be moved to non full hospitals and because of interrupted links which result in a decrease in the transportation speed. The first study proposes the distance covered by each casualty, defined in probabilistic terms, as a meaningful system performance measure. Comparison between the distance distributions after an earthquake (accounting for damage to hospitals and road network, as well as for casualties and congestion), under different seismic retrofit/upgrade scenarios with the baseline distribution gives useful indications for the allocation of resources.

Examples of Level II studies are those in Shinozuka et al. (2003) and Chang et al. (2011). The approach in Shinozuka et al. (2003) aims at the determination of direct and indirect economic loss due to damage to a transportation network. Direct loss is related to physical damage to vulnerable components, while indirect loss is related to functionality of the system, whose degradation is measured in terms of a system-level performance index called Driver's delay (DD), i.e., the increase in total daily travel time for all travelers. Indirect loss is expressed as the DD times a unit cost of time. Traffic flows are evaluated by equilibrium analysis under a static origin-destination matrix. The vulnerable components are the bridges within the network, for which four states of increasing damage, namely minor, moderate, major and collapse, with corresponding fragilities are employed. The state of each link, corresponding to a different residual traffic capacity, equals that of its most severely damaged bridge. Total DD is obtained by summing the values for all days over which the delay persists. However, the DD decreases over time due to repair activity taking place after the event, modeled in an admittedly over-simplified manner. This study is extended in Zhou et al. (2004), to consider the effect of retrofit strategies in improving the performance in future events.

The work by Chang et al. (2011) advances a proposal for going beyond the use of the pre-earthquake (static) origin-destination matrix as an input for traffic flow analysis. The post-quake travel demand is complicated and the change of traffic pattern after the event is coupled with the damage of transportation infrastructures. To arrive at a new origin-destination matrix the paper modifies the trip generation and trip distribution stages (the first two stages of the so-called sequential procedure) of a traffic analysis to accommodate for earthquake-induced damage. Traffic Analysis Zones (TAZs) are classified into four types, depending on the presence of attractants (e.g., hospitals or emergency shelter) and repellents (e.g., hazardous materials (HAZMAT) release, fire following earthquake, or damaged facilities). Then the pre-earthquake travel demand of each TAZ is modified according to the classification. Several general assumptions are made on post-earthquake travel behavior and emergency traffic management measures. The paper reports also an extensive literature review on attempts to model traffic pattern changes in the aftermath of an earthquake.

Finally, among the few available Level III studies, an example is the work by Karaca (2005). The work reports a regional earthquake loss methodology that emphasizes economic interdependencies at regional and national scales and the mediating role of the transportation network. In an application to the Central U.S. under threat from earthquakes from the New Madrid Seismic Zone, regional and national losses from scenario earthquakes are evaluated, together with a quantification of the corresponding uncertainty including contributions from seismicity, attenuation, fragilities, etc. The effectiveness of alternative mitigation strategies is also considered. The loss assessment methodology includes spatial interactions (through the transportation network) and business interaction (through an input-output model) and extends geographically to the entire conterminous U.S. The losses reflect damage to buildings and transportation components, reduced functionality, changes in the
level of economic activity in different economic sectors and geographical regions, and the speed of the reconstruction/recovery process. Evaluation of losses for a number of scenario earthquakes indicates that losses from business interruption may be as significant as infrastructure repair costs.

In the frame of the present SYNER-G application a level I analysis has been performed, focusing the attention on the network’s pure connectivity.

5.2 SYSTEMIC VULNERABILITY METHODOLOGY AND SOFTWARE IMPLEMENTATION

5.2.1 Systemic vulnerability methodology and performance indicators

The modeling and the analysis of a transportation network for the purpose of seismic performance assessment rely on tools and methods of increasing complexity depending on the adopted approach. Level I studies require a simple description of the network in terms of a graph and analysis tools are limited to basic graph theory results. Level II and III studies require additional information and specialized algorithms for the determination of traffic flows on the congested, damaged network.

With reference to an undamaged road network, i.e., non-seismic conditions, different models exist in the literature for performing a level II or level III study. In such conditions, the computation of the origin-destination matrix, the edge flows and congested travel times are straightforward.

On the other hand, the literature lacks traffic demand models for a road network in an area hit by an earthquake. In this case, the number of attracted and generated trips for each TAZ should ideally be estimated according to people’s accessibility to the RDN and their needs in the emergency post-earthquake phase; consequently, the pattern of travel demand is likely to be completely different from that in the normal operating conditions. Development of such a model was not pursued within SYNER-G and remains as a fundamental research need. For this reason, it has been decided to perform a level I analysis, focusing the attention on the functioning of the network in terms of pure connectivity.

A road network can be represented as a graph consisting of a set $V$ of $n$ nodes or vertices, connected by a set $A$ of $n_a$ arcs, or links or edges. Several alternative representations are in use to describe the relationship between nodes and arcs. One common choice is in terms of the adjacency matrix $B = [b_{ij}]$, which is a $n \times n$ Boolean square matrix, whose terms are either 0, when no connection exists between nodes $i$ and $j$, or 1 when a connection exists. Another Boolean matrix representation is in terms of the $n \times n_a$ incidence matrix. If a graph is directed (also known as digraph), the existence of a link from nodes $i$ to $j$ does not imply the presence of a link between nodes $j$ and $i$ (e.g. some roads are one-way only); in this case, the adjacency matrix is not symmetric. When for every directed arc the opposite one exists, the graph is said to be symmetric, or non-directed or simply a graph. In many applications it is useful to associate to nodes or links of a graph some additional information or weights (e.g. the length of the link, the free flow speed, etc.). When this is the case one speaks of labelled graphs. When the graph is described in terms of the adjacency matrix $B$, the additional information can be either included in this matrix, if it is a simple scalar (e.g. the arc length), or stored separately. Given a graph, a finite or infinite sequence of links such that the origin node of each arc coincides with the destination node of the previous one is called
a path \( P \). The order of the path is the number \( n_p \) of links making up the path. A path is called \textit{simple} when it is made up of distinct arcs, and \textit{elementary} when it passes through distinct nodes.

With reference to directed graphs, two different types of connectivity are involved: strong and weak. The difference is in the fact that the latter does not consider the edges directions, actually treating the network as non-directed. Of course, for non-directed graphs only the weak connectivity can be considered. In general, a graph is composed of one or more (strongly or weakly) connected components (i.e., groups of connected nodes).

A \textit{bridge} (also known as a cut-edge or cut-arc or an isthmus) is an edge whose deletion increases the number of connected components.

An \textit{articulation point} (also known as a cut-vertex) is any node that when removed increases the number of connected components.

The quantitative measure of the RDN performance subjected to a seismic hazard is given by Performance Indicators (PIs) that 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”). A detailed discussion on performance indicators adopted in the SYNER-G general methodology for the RDN is included in report D2.6. In the following is reported for reference a list of those computed in this application.

\textbf{System-level PIs}

- \textbf{Simple Connectivity Loss}, or \textit{SCL} [deterministic, connectivity modeling] (Poljanšek \textit{et al.} 2011). This index, whose definition is based on the concept of connectivity, for a generic system measures the average reduction in the ability of sinks to receive flow from sources:

\[
SCL = 1 - \frac{N'_s}{N'_s/N'_0},
\]

where \( \langle \cdot \rangle \) denotes averaging over all sink vertices, while \( N'_s \) and \( N'_0 \) are the number of sources connected to the \( i \)-th sink in the seismically damaged network and in non-seismic conditions, respectively. With reference to an RDN, all the single TAZs, taken one at a time, are considered sinks, whereas all the remaining TAZs are sources.

- \textbf{Weighted Connectivity Loss}, or \textit{WCL} [deterministic, connectivity modeling]. This index upgrades the simple connectivity loss by weighting the number of sources connected to the \( i \)-th sink, in the seismically damaged network and in non-seismic conditions, respectively:

\[
WCL = 1 - \frac{(N'_s \cdot W'_s) / (N'_0 \cdot W'_0)}
\]

where the weights \( W'_s \) and \( W'_0 \) can be defined in different ways. The authors here defined them as the sum of the inverse of travel times of the single paths between the \( i \)-th sink and the sources, in the seismically damaged network and in non-seismic conditions, respectively:

\[
W'_i = \sum_{j,i} l_{ij} \cdot \frac{1}{T_{ij}}
\]
$I_{ij}$ is the indicator function (indicating the existence of a path between the $i$-th sink and the $j$-th source), $TT_{ij}$ is the travel time of the path between the $i$-th sink and the $j$-th source and $j$ spans all the source nodes, i.e., all TAZs excluded the $i$-th one.

- **Moving average $\mu$ and moving standard deviation $\sigma$ of SCL and WCL.** [probabilistic, connectivity modeling]. These parameters represent the evolution of the expected value and the standard deviation of the PIs during the simulation, until the current run.

- **Mean Annual Frequency (MAF) of exceedance of SCL and WCL.** [probabilistic, connectivity modeling]. The MAF of the generic performance measure $Y$ exceeding threshold value $y$ is computed as:

$$\lambda_\nu(y) = \sum_i \lambda_\nu_{ij} G_{yij}(y) = \sum_i \lambda_\nu G_{yi}(y) = \lambda_\nu G_Y(y)$$

(5.4)

by post-processing of the vector of sampled values of $Y$ to first obtain the complementary (experimental) distribution function $G_Y(y)$. Then this distribution is multiplied by the MAF of all earthquakes in the region, $\lambda_0 = \sum_i \lambda_{0ij}$. The probability $p_i = \frac{\lambda_{0ij}}{\lambda_0}$ that, given an earthquake, it occurs on source $i$ is respected in the complementary distribution $G_y(y)$ where results come from events sampled in the correct proportion among the different sources.

**Component-level PIs**

- **Minimum travel time** [deterministic/probabilistic, connectivity modeling], needed to reach one of the hospitals, computed for each TAZ centroid. It can be computed both for each scenario and as averaged on the whole simulation, which is why it can be considered both deterministic and probabilistic.

- **Terminal Reliability** [probabilistic, connectivity modeling], indicating the probability that a path exists between a specific OD pair. This probability is given by the expected value of the indicator function, assigned to the generic OD pair during the simulation.

### 5.2.2 Software implementation

As addressed in SYNER-G report D2.1 (Franchin et al. 2011), the object-oriented paradigm (OOP) has been adopted for the purpose of modeling the Infrastructure and the seismic hazard acting upon it. Within the OOP, in abstract terms, the problem is described as a set of objects, characterized in terms of attributes (or properties) and methods that interact with each other. Objects are instances (concrete realizations) of classes (abstract models, or templates for all objects with the same set of properties and methods).

The SYNER-G prototype software includes an object-oriented representation of a subset of all the systems in the taxonomy, among which is the road network. In the following are reported the properties and methods of the RDN class and its subclasses.
**The RDN class**

Fig. 5.1 illustrates the RDN class diagram. The RDN is modeled as a *directed* graph, i.e., a graph in which all edges have a travelling direction, from node \( i \) to node \( j \). For this reason, the RDN class is considered as a subclass of the *Directed* abstract class, which in turn is a subclass of the *Network* abstract class.

![Class diagram for the RDN class](image)

Similar to other Network classes, a road network is made up of *nodes* and *links/edges* connecting them. As a consequence, the RDN class is the composition of the *RDNnode* and *RDNedge* abstract classes. The first is the generalization of the TAZ, ExternalStation and Intersection classes. A brief explanation of these node typologies is given in Deliverable D5.5. The *RDNedge* class is the generalization of the RoadSegment, Embankment, Trench, UnstableSlope, RDNtunnel and Bridge classes. The definition of these edge typologies is given in SYNER-G reports D3.6 (Fardis et al. 2011) and D3.7 (Kaynia et al. 2011), where the "road pavement" typology corresponds to the RoadSegment class.

The following is the list of properties of the RDN class, with names following the naming convention adopted for variables in developing the prototype software, whereby multi-word names have no blank spaces in between words and the latter are separated by capitalizing the initial letter of each word. The list is split into five parts:

**List of pointers**

- **parent**: this is a pointer to the parent object which, in this case, is the Infrastructure (the object from the Infrastructure class)
- **road**: pointers to all the road pavements in the system, objects from the RoadSegment class
- **embank**: pointers to all embankments, objects from the Embankment class
o **trench:** pointers to all trenches, objects from the Trench class
o **unstSlope:** pointers to all unstable slopes, objects from the UnstableSlope class
o **tunnel:** pointers to all tunnels, objects from the RDNtunnel class
o **bridge:** pointers to all bridges, objects from the Bridge class
o **taz:** pointers to all TAZs, objects from the TAZ class
o **intersection:** pointers to all intersections, objects from the Intersection class
o **external:** pointers to all external stations, objects from the ExternalStation class

**Road network global properties**

- **nEdges:** number of links or edges in the RDN
- **nNodes:** number of nodes in the RDN
- **dependency:** list of dependent edges, i.e., those edges sharing the component (e.g., an embankment) with the reference edge (edge defined in the input file). Whenever a damage state is sampled during simulation, these edges are assigned the same damage state of the reference edge. Since the graph describing the RDN is a directed one, whenever the road between two nodes is a two-way road, two edges are created in the graph ($ij$ and $ji$). This “dependency” feature is used to avoid inconsistent damage states for lanes running in different directions over the same road element (typically bridges)
- **edges:** connectivity matrix of the RDN listing the start and end nodes of each edge
- **lowOrderRoadWidth:** average width of low-order roads (i.e., those not explicitly modeled in the network). This as well as the following properties are employed in the road blockage model to compute buildings’ accessibility to the RDN
- **distanceBDG_lowOrderRoad:** average distance between buildings and low order roads
- **roadBlockageModel:** road blockage model to be used for low order roads
- **roadBlockageCoefficients:** coefficients of road blockage model (low order roads)
- **edgeWidth:** width of edges for primary roads, modeled in the network (road blockage model)
- **edgeDistanceToBDG:** average distance of edges’ centroids to buildings for primary roads (road blockage model)
- **edgeHierarchy:** importance of edges related to width, distance to buildings etc (road blockage model)
- **edgeAdjacentBDG:** presence of buildings along the road, with values no buildings, one side, both sides (road blockage model)
- **lengthInCells:** length of segments of edges intersecting built cells (road blockage model)
- **vulnSites:** list of vulnerable sites (components) of the RDN, containing their location and IM type(s)
- **adjacencyMatrix**: $n \times n$ Boolean square matrix, whose terms are either 0, when no connection exists between nodes $i$ and $j$, or 1 when a connection exists.

- **incidenceMatrix**: for a directed graph, $n \times n_a$ matrix, whose terms are -1 if the edge $j$ leaves the node $i$, 1 if it enters node $i$, 0 otherwise.

- **incidenceList**: a list storing all the edges converging to the different nodes.

- **deadEnds**: list of network dead ends.

- **articPTS**: list of network articulation points (a graph-theoretic notion: nodes whose removal increases the number of connected sub-networks).

- **bridges**: list of network bridges (not physical bridges but graph theory bridges, i.e., edges whose removal increases the number of connected sub-networks).

---

**Edge and node properties (many of these properties have counterparts in the RDNedge and RDN node classes. Those in this class are vectors collecting values that are also stored individually within each node and edge object)**

- **edgeVs30**: Vs30 value at the edges’ centroid.

- **edgeType**: typology of edges.

- **edgeClass**: class of edges (minor, principal or highway).

- **edgeCapacity**

- **edgeFreeFlowSpeed**

- **edgeFreeFlowTT**: free flow travel time of edges.

- **edgeNumWays**: number of ways (1 or 2) of edges (if 1, the edge is inserted from $i$ to $j$ only).

- **edgeNumVulnEl**: number of vulnerable elements (1 or 2) for two-ways edges.

- **edgeIsVulnerable**: flag indicating if the generic edge is considered vulnerable or not.

- **edgeIMType**: intensity measure used in the fragility of the edge.

- **edgeCentroidPosition**

- **edgeLength**

- **edgeSiteClass**: site class at the edge centroid sites according to the site amplification method to be used (valid for all *a posteriori* amplification methods, see Section 5.3.2).

- **edgeDepth2GW**: depth of the groundwater at the edge centroid site.

- **edgeLiqSusClass**: liquefaction susceptibility of the edge centroid site.

- **edgeLandSusClass**: landsliding susceptibility of the edge centroid site.

- **edgeYieldAcc**: yielding or critical acceleration for landsliding at the edge centroid site.

- **nodePosition**

- **nodeAltitude**

- **TAZtype**: TAZ type, CBD (Central Business District) or non-CBD.
**Properties that record the state of the RDN for each event**

- **states**: $n_E \times 1$ collection of properties that describe the current state for each of the $n_E$ events
  - **SCL**: Simple Connectivity Loss, first system-level performance indicator
  - **WCL**: Weighted Connectivity Loss, second system-level performance indicator
  - **mean_SCL**: moving average of SCL over the simulation, until the current run
  - **mean_WCL**: moving average of WCL over the simulation, until the current run
  - **mean_TRUNC**: probability of disconnection of TAZs from each other
  - **std_SCL**: moving standard deviation of SCL over the simulation, until the current run
  - **std_WCL**: moving standard deviation of WCL over the simulation, until the current run
  - **adjUpdated**: updated adjacency matrix, taking into account the network damage
  - **numSources**: number of TAZs connected to the single TAZs
  - **numSourcesW**: number of TAZs connected to the single TAZs, weighted by the number of edges composing the paths
  - **numGroups**: number of node groups composing the network
  - **belong2group**: number of the group which the single nodes belong to

**Properties that store the global performance of the RDN at the end of simulation**

- **MAF**: Mean Annual Frequency of exceedance values for the considered system-level PIs

The following is the list of the main methods of the RDN class (some of these are briefly explained):

- **anySDFS**: performs the Depth First Search algorithm, in order to know which vertices can be reached by a path starting from any source
- **computeCovMean**: computes coefficient of variation and moving average of performance indicators (in Monte Carlo simulations)
- **computeCovMeanIS**: computes coefficient of variation and moving average of performance indicators (in Importance Sampling simulations)
- **addSecondEdge**: adds a second edge in the model from node $j$ to node $i$ for two-way roads
- **evaluateRDNdamage**: computes components’ damage state. If such damage state is the most severe (i.e., collapse), then the component is set to broken and successively deleted from the network
- **computePerformanceIndicator**
- **stronglyConnectedNodes**
- **weaklyConnectedNodes**
- **discretizeEdges**: subdivides all edges with length larger than a threshold into smaller segments, so as to allow a more refined computation of edges intensity measure(s) and, consequently, damage
- **edges2Adjacency**: perform corresponding transformation
- **edges2IncidenceList**: perform corresponding transformation
- **edges2IncidenceMatrix**: perform corresponding transformation
- **findDeadEnds**
- **getListOfLists**
- **isStronglyConnected**: determines whether a path exists between any two nodes in a directed graph (accounts for edge direction)
- **isWeaklyConnected**: determines whether a path exists between any two nodes in an undirected graph
- **minPath**: finds the minimum path between a pair of nodes
- **retrieveLandSusEdges**
- **retrieveLiqSusEdges**
- **retrieveSiteClassEdges**
- **retrieveSiteClassNodes**
- **retrieveVs30edges**
- **retrieveVs30nodes**
- **retrieveYieldAccEdges**
- **subNetwork**: finds the list of edges connecting an input list of nodes
- **updateConnectivity**: based on the network damage for the generic event, sets to 0 the elements in the adjacency matrix corresponding to broken edges and checks if TAZs are isolated from each other.
- **setRoadBlockageModel**
- **getEdgeLength**
- **evaluateRDNblockage**: predicts if primary roads (i.e., those roads modeled in the software) are blocked by debris due to building collapse (if buildings are
modeled into the Infrastructure), based on road width, distance to buildings, hierarchy etc.

**The RDNedge class and subclasses**

The following is the list of properties of the *RDNedge* abstract class. These properties are common to all subclasses of this class.

- **parent**: this is a pointer to the parent object which is in this case the road network (the object from the RDN class)
- **siteClass**: site class at the edge centroid site according to the site amplification method to be used (valid for all *a posteriori* amplification methods, see Section 5.3.2)
- **connectivity**: start and end node of the edge
- **centroid**: edge centroid location
- **type**: edge typology, defining the component fragility functions
- **class**: either minor, principal or highway, according to the edge free flow speed
- **capacity**: in terms of vehicles per hour (vph)
- **freeFlowSpeed**
- **numWays**: either 1 or 2; if set to 2, the edge is taken as reference for a second (dependent) edge in the opposite direction
- **numVulnEl**: if set to 1, with # of ways set to 2, the same damage state is assigned to both edges
- **refEdge**: pointer to reference edge (for dependent edges)
- **L**: edge length
- **Vs30**: Vs30 at edge centroid
- **isVulnerable**
- **IMType**
- **depth2GW**
- **liqSusClass**
- **landSusClass**
- **yieldAcc**
- **states**: $n_E \times 1$ collection of properties that describe the current state for each of the $n_E$ events
  - **broken**: flag indicating if the edge is broken
  - **blocked**: flag indicating if the edge is blocked by debris due to building collapse (this property only if buildings are part of the general Infrastructure model and remain empty when a simple RDN-only analysis is performed)
- **primaryIM**: primary intensity measure at edge centroid, as interpolated from the regular grid points
- **localIMs**: secondary or local intensity measures, correlated to the primary IM
The RDNEdge abstract class and its subclasses do not have any methods (only the object
constructor for the concrete subclasses).

The RDNNode class and subclasses

The following is the list of properties of the RDNNode abstract class. These properties are
common to all subclasses (TAZ, ExternalStation and Intersection) of this class.

- **parent**: this is a pointer to the parent object which is in this case the road network
  (the object from the RDN class)
- **position**: node location
- **altitude**: node altitude
- **Vs30**: Vs30 at node
- **isVulnerable**
- **IMType**
- **states**: $n_E \times 1$ collection of properties that describe the current state for each of the
  $n_E$ events (only for TAZ objects)
  - **isolated**: flag indicating if the TAZ is isolated from all the others
  - **TR**: vector of flags (0/1) indicating if the TAZ is connected to the single TAZs

The subclass ExternalStation has one further property, i.e., tazType. The subclass TAZ has
five further properties, i.e., tazType, refCells, totalHouseholds, totalEmployment,
employmentPerPurpose, that objects of this subclass do not share with those of the other
subclasses. Such properties are used only for a capacitive analysis of the road network and
contain information related to the number of households and employed people living in the
BDG system tributary cells of each TAZ. These properties are used in the trip generation
stage if an origin-destination matrix is not supplied as an input to the analysis.

The RDNNode abstract class and its subclasses do not have any methods (only the object
constructor for the concrete subclasses).

5.3 THE CASE STUDY

5.3.1 General description

The road network of Calabria region, in Southern Italy, has been chosen as the case study.
Significant earthquakes have not affected the region in recent times; hence the study
represents a real scale application to test the capabilities of the SYNER-G methodology and
software rather than a validation study against real data.

The original data available for the road network of Calabria (database DBPrior10k, provided
by the Cartographic Center of Calabria region, http://www.centrocartografico.it/) included the
network topology, population of the cities and suburbs served by the network, as well as the
regional hospitals’ positions. In particular, the topological data consisted of:
2,451 TAZs (corresponding to either municipalities or suburbs) and 3,607 intersections, for a total of 6,058 nodes;

13,956 edges, divided into main and secondary roads (based on free-flow speed) and connectors of TAZs to the road network (these latter are used since in the available data set the TAZs have not been moved to the nearest network node);

Further available data, provided by Borzi and Fiorini (2012), included the positions of 1,325 bridges (for few of them fragility functions were available) and the positions and landsliding susceptibility of 9,002 landslide susceptible areas.

5.3.2 Seismic hazard

The seismic hazard is modeled through 20 faults taken from the Italian DISS (Database of Individual Seismogenic Sources) database, employing the truncated Gutenberg&Richter recurrence model for the source activity (Fig. 5.2).

![DISS database faults affecting Calabria](http://www.opensha.org/)

Fig. 5.2 DISS database faults affecting Calabria

Within the DISS source model, also used in the European SHARE fault database, the fault surface does not correspond to a simple rectangle (seismogenic area), but is described as a more complex polygon that can change strike according to the trace. The current fault typology used within the SYNER-G model and the prototype software implementation for shallow faults in Europe (except the Aegean, Calabrian and Cypriot subduction interfaces) is simpleFaultGeometry. The fault is described by a trace, a dip and an upper and lower depth (the dip direction is always 90° clockwise from the azimuth to the last point on the trace from the first point of the trace). The rendering of an evenly-spaced discrete mesh over the fault surface is done using an adaptation of the algorithm of Mark Stirling, which is what is currently implemented in OpenSHA (Open Source Seismic Hazard Analysis [http://www.opensha.org/]). The fault source, as it is represented in this fashion, is equivalent to a composite source (see Weatherhill et al. 2011).

The ground motion prediction equation (GMPE) employed in this application is that by Akkar and Bommer (2010).
The primary IM (in this case PGA) is computed at the points of a regular grid. PGA is then retrieved at vulnerable sites by distance-based interpolation and finally the local IM (if not coinciding with primary) is sampled conditionally on primary IM. Since PGD is needed as an input to the fragility model of road segments, the landslides and co-seismic rupture models in the geotechnical hazard module are used.

Amplification takes place afterwards. Different amplification methods are available: Eurocode 8, NEHRP, Choi&Stewart, context-specific. Such methods amplify the shaking intensity measure (IM) at vulnerable sites \textit{a posteriori}, i.e., after the ground motion calculation stage. It can also be used within-GMPE amplification method, using the Vs30 values for site classification. However, no soil classification data are available and, hence, IM values are computed on rock.

The final step, when needed, is the conditional sampling of the PGD from the relevant geotechnical hazard model. A detailed description of the entire hazard model adopted in the methodology and hence implemented in the SYNER-G prototype software can be found in Cavalieri et al. (2012) and SYNER-G reports D2.1 (Franchin et al. 2011) and D2.13 (Weatherhill et al. 2011).

5.3.3 System topology and characteristics

Many of the original available data appeared irrelevant at the regional scale. Moreover, the required computational effort was cumbersome, making it impossible to run a simulation by using the SYNER-G prototype software which is written in the interpreted MATLAB language. For these reasons, it has been decided to reduce the available data set to a manageable yet still important size, without compromising the nature of the study, i.e., application to a real case.

The data reduction process consisted of several steps:

- Removal of many TAZs, corresponding to suburbs having a very small population. Their population has been aggregated into that of the corresponding municipalities. Only municipalities have been kept, reducing the number of TAZs to 422 (Fig. 5.3);
- Removal of bridges with lengths less than 35 m (which is the upper bound value for the length of prefabricated pre-stressed concrete girders usually employed in Italy in the decades from the 1960s for ordinary viaducts; bridges with shorter length are likely to be simple single-span bridges which, due to usually large seating lengths in the Italian practice, have been considered non vulnerable), resulting in a total of 521 bridges, 11 of which characterized by detailed fragility data;
- Removal of inactive landslides areas, resulting in a total of 2,089 areas;
- Displacement of TAZs to the nearest road network node and removal of corresponding connectors, not affecting network connectivity;
- Integration of bridges into the graph, since graph and bridges belonged to two different databases; bridges are considered in the software as edges; each bridge has been projected onto the road segment with the closest centroid;
- Removal of secondary roads not included in minimum paths connecting TAZs to main roads; a minimum path in this case is the path with the minimum travel time;
Removal of all dead ends resulting from the previous steps.

The results of the data reduction process can be seen in Fig. 5.4, showing a close-up on the network topology, before (left) and after (right) the reduction.

The resulting road network is composed of 2,861 nodes and 5,970 edges (Fig. 5.5, left). The nodes are subdivided into 422 Traffic Analysis Zone (TAZ) centroids and simple intersections. Edges, that are the only vulnerable components in the network, are subdivided into road segments and bridges, with fragility models expressed in terms of permanent ground displacement (PGD) and peak ground acceleration (PGA), respectively. Edges are also classified as either main roads (principal roads or highways) or secondary roads, based
on their free flow speed. It is recalled that within the developed model the RDN is modeled as a directed graph and all edges have a travelling direction, from node \( i \) to node \( j \). For this particular network, all edges are two-ways roads, effectively making the graph undirected. Finally, the graph is a weighted one, with weights being the free flow travel times of edges. Further available data include the location of the ten public hospitals, belonging to the regional health-care system, as well as of the landslide susceptible areas (Fig. 5.5, right).

![Fig. 5.5 Road network topology (left) and location of hospitals and landslides areas (right)](image)

### 5.3.4 Description of the input

The MATLAB environment provides through the function `xlsread` the capability of importing data organized within an Excel workbook. The latter was chosen as the format of the input file for the prototype software. Input is prepared as a workbook within which, in general, each sheet correspond to a different system in the SYNER-G taxonomy.

The first two cells in the `rdn` sheet specify the number of edges (sides) and of nodes, 2,985 and 2,861, respectively. It should be noted that the user has to input only one (directed) edge per couple of nodes. If the corresponding road is a two-ways one, the software will add the second edge automatically. The `want discretization` and following fields contain values used to (if the former parameter is assigned a “yes” value) discretize too long edges into a number of smaller roads to improve the computation of roads’ damage (each sub-segment is considered as a separate vulnerable element, with the IM evaluated at the segment centroid).

The next rows, after the `nodes` keyword, specify in a standardized way (similar for all network/line-like systems) the nodes of the system. In particular the information to be provided for each node is in the order: localization, site properties, functional and related to seismic damageability. Localization is given in terms of latitude and longitude in degrees and altitude above sea level in meters. The site properties are specified in terms of average shear wave velocity \( V_{s30} \). It can be noted from the figure that \( V_{s30} \) is set to a very high value \( (1,000 \text{ m/s}) \) for all nodes, meaning rock sites; in fact, for values higher than 750 m/s the software considers the sites to be on rock and does not amplify their local IM. Functional
information for the node of an RDN is the type of node (either a TAZ, an external station or an intersection) and the type of TAZ (either CBD or non-CBD). The next two columns specify whether the node is vulnerable, and in case it is, which is the IM(s) to be input to the corresponding fragility model. The last column reports the population of each TAZ (corresponding to a municipality).

The next part of the rdn sheet, after the sides keyword, specifies in a standardized way (similar for all network/line-like systems) the sides/edges of the system. In particular, the first two columns specify the edge connectivity (start and end nodes). The site properties are specified in terms of Vs30, site class, depth to groundwater in feet, liquefaction and landslides susceptibility class, yield acceleration. It can be noted that the fields specifying landslides susceptibility class and yield acceleration are left empty for all edges. This is because landslides areas are read from a GIS shape file, and hence landslides susceptibility class and yield acceleration are automatically assigned. Functional information includes the edge typology (with a final letter or number indicating the sub-typology and, consequently, the particular set of fragility functions to be used), the class (minor, principal or highway), the capacity in vph (vehicles per hour), the free flow speed in km/h, the number of ways (1 or 2) and the number of vulnerable elements for two ways roads (1 element to be shared or 2 distinct elements).

As for the nodes, two columns specify whether the edge is vulnerable, and in case it is, which is the IM(s) to be input to the corresponding fragility model.

### 5.4 RESULTS

Three types of simulations have been carried out: a plain Monte Carlo (MCS) and two improved simulations employing variance reduction techniques, i.e., Importance Sampling (ISS) and Importance Sampling with k-means clustering (ISS-KM). The reader can refer to SYNER-G report D2.1 (Franchin et al. 2011) for an exhaustive description of such simulation schemes.

![Fig. 5.6 Moving average $\mu$, $\mu+\sigma$ and $\mu-\sigma$ curves for SCL (left) and WCL (right)](image-url)
The analysis results as obtained from a plain MCS of 20,000 runs are presented in the following figures. The chosen number of runs have been shown to yield stable estimates for all considered PIs.

Fig. 5.6 shows the moving average \( \mu \) curves for SCL (left) and WCL (right), as well as the \( \mu + \sigma \) and \( \mu - \sigma \) curves for the two PIs. The figure indicates that the expected value of connectivity loss given the occurrence of an earthquake is higher for WCL than for SCL, as expected. In fact, WCL takes into account not only the existence of a path between two TAZs, but also the increase in travel time due to the seismically induced damage suffered by the RDN. The jumps present in the plots are located in correspondence of simulation runs/samples in which at least one TAZ results disconnected from at least one TAZ, leading SCL and WCL to yield values greater than 0.

Fig. 5.7, left, shows the MAF of exceedance curves for SCL and WCL. As expected, weighting the computation of connectivity loss with the path travel times yields higher values of exceedance frequency.

Fig. 5.7, right, displays, in a matrix form with a grey scale, the values of TR for each pair of TAZs. The matrix, which is symmetric due to the graph being undirected (recall that even if the model is directed this particular network is in practice undirected because there is always a pair of opposite edges between connected nodes, sharing the same vulnerability), indicates that the probability of connection is very high over all the region, with lower reliability concentrated in the northern part of Calabria (approximately the first 100 TAZs).

Fig. 5.8, left, shows the contour map of travel time to the closest hospital for the entire region, in non-seismic or undamaged conditions. The blue “islands”, with zero travel time, clearly indicate the hospitals’ positions in the region.

Fig. 5.8, right, shows the contour map of expected travel time increment in damaged conditions, obtained dividing the expected value of minimum travel time in seismic conditions (averaged on the whole simulation) by the reference minimum travel time. Such increment results to be very low and concentrated in the central mountainous part of the region.
With reference to some PIs, the results coming from MCS have been taken as the reference solution and compared with those obtained from the two variance reduction techniques, ISS (2,000 runs) and ISS-KM (200 runs). In particular, in Fig. 5.9 the comparison is relative to moving average curves of SCL (left) and WCL (right), while in Fig. 5.10 it is referred to MAF curves of the same indicators. The match of the curves is shown to be quite good in all cases, with comparable orders of magnitude. The authors tested the efficacy of ISS and ISS-KM with reference to some case studies (mostly buildings and networks) and some particular PIs, noting that the results of such tests were fully satisfactory only in some cases. The conclusion has been that the effectiveness is strongly case-dependent and PI-dependent. Further studies on different systems analyzed with different approaches (connectivity/capacitive) are needed to draw guidelines for the use of such variance reduction techniques as a practical alternative to the cumbersome and time-consuming MCS.
5.5 CONCLUSIONS

The SYNER-G methodology has been applied to the road network of Calabria region, in Southern Italy. Significant earthquakes have not affected the region in recent times; hence the study represents a real scale application to test the capabilities of the developed methodology and software rather than a validation study against real data.

A level I analysis has been performed, focusing the attention on the network’s pure connectivity.

The road network and the seismic hazard acting upon it are modeled in the SYNER-G prototype software through the object-oriented paradigm, very efficient in allowing to avoid code duplication and in making the whole code modular.

Three types of simulation have been carried out (plain Monte Carlo (MCS), Importance Sampling (ISS) and Importance Sampling with k-means clustering (ISS-KM)), computing within each of them a number of performance indicators.

With reference to some PIs, the results coming from MCS have been taken as the reference solution and compared with those obtained from the two variance reduction techniques, ISS (2,000 runs) and ISS-KM (200 runs). The match of the curves is shown to be quite good in all cases, but since the efficacy of ISS and ISS-KM has been seen to be strongly case-dependent and PI-dependent, further studies on different systems analyzed with different approaches (connectivity/capacitive) are needed to draw guidelines for the use of such variance reduction techniques as a practical alternative to the cumbersome and time-consuming MCS.
6 Application and validation study to an electric power network in Italy

6.1 INTRODUCTION

A modern Electric Power Network (EPN) is a complex interconnected system that can be subdivided into four major parts:

- Generation
- Transformation
- Transmission and Distribution
- Loads

These are briefly described in the following. The interested reader can also see Saadat (2002).

Generation of electric power is carried out in power plants. A power plant is composed of several three-phase AC (Alternate Current) generators known as synchronous generators or alternators. Synchronous generators have two synchronously rotating fields, one of which is produced by the rotor driven at synchronous speed and excited by DC (Direct Current), while the second one is produced in the stator windings by the three-phase armature currents. The DC current for the rotor windings is provided by the excitation systems, which maintain generator voltage and control the reactive power flow. Because of the absence of the commutator, AC generators can generate high power at high voltage, typically 30 kV. In a power plant, the size of generators can vary from 50 MW to 1500 MW.

At the time when the first EPNs were established in the world, individual electric companies were operating at different frequencies anywhere, in US ranging from 25 Hz to 133 Hz. As the need for interconnection and parallel operation became evident, a standard frequency of 60 Hz was adopted throughout the US and Canada, while most European countries selected the 50 Hz system. These two AC frequencies are still in use at the present time.

The source of the mechanical power, commonly named “prime mover”, may be hydraulic turbines at waterfalls, steam turbines whose energy comes from the burning of coal, gas and nuclear fuel, gas turbines or occasionally internal combustion engines burning oil. Many alternative energy sources, like solar power, geothermal power, wind power, tidal power and biomass, are also employed.

One of the major components of a power network is the transformer, which transfers power with very high efficiency from one level of voltage to another level. The power transferred to the secondary winding is almost the same as the primary, except for losses in the transformer. Therefore, using a step-up transformer of voltage ratio $a$ will reduce the secondary current of a ratio $1/a$, reducing losses in the line, which are inversely proportional to voltage and directly proportional to distance. This makes the transmission of power over long distances possible. At the receiving end of the transmission lines step-down transformers are used to reduce the voltage to suitable values for distribution or utilization.
The purpose of a power delivery system, also known as transmission and distribution (T&D) system, is to transfer electric energy from generating units at various locations to the customers demanding the loads.

A T&D system is divided into two general tiers: a transmission system that spans long distances at high voltages on the order of hundred of kilovolts (kV), usually between 60 and 750 kV, and a more local distribution system at intermediate voltages. The latter is further divided into a medium voltage distribution system, at voltages in the low tens of kV, and a low voltage distribution system, which consists of the wires that directly connect most domestic and small commercial customers, at voltages in the 220-240 V range for Europe. The distribution system can be both overhead and underground.

The transmission and distribution systems are generally characterized by two different topological structures: the transmission system is an interconnected redundant grid, composed of stations as nodes and transmission lines as edges, while the distribution system is a tree-like network, following the main streets in a city and reaching the end users. Fig. 6.1 shows the two topological structures.

![Fig. 6.1 Typical topological structures, grid-like (on the left) and tree-like (on the right), respectively for transmission and distribution systems](image)

The lines at different voltages are terminated in substations. In general, an electric substation is a facility that serves as a source of energy supply for the local distribution area in which it is located, and has the following main functions:

- Changing voltage from one level to another, by means of transformers.
- Delivering power.
- Providing points where safety devices such as disconnect switches, circuit breakers, and other equipment can be installed.
- Regulating voltage to compensate for system voltage changes.
- Eliminating lightning and switching surges from the system.
- Converting AC to DC and DC to AC, as needed.
- Changing frequency, as needed.

Depending on their functions, substations can be grouped into three typologies, in particular:
1. Transformation substations.
2. Distribution substations.
3. Transformation/distribution substations.

An important component inside a substation is the bus, a *redundant system of bars* (generally two bar systems form a bus, with the second one being provided for the purpose of maintenance operations) transferring energy between lines entering or exiting from the station. When the transformation function is required (type 1 and 3 above), two buses at two different voltages are present. For type 3 only, where also power delivery is required, one or both buses are load buses. For distribution substations, the only bus present is a load bus. Buses are the network nodes.

Substations layouts are extremely variable. They can be entirely enclosed in buildings where all the equipment is assembled into one metal clad unit. Other substations have step-down transformers, high voltage switches, oil circuit breakers, and lightning arresters located outside the substation building.

The electric power is delivered to the single customers through distribution circuits, which include poles, wires, in-line equipment, utility-owned equipment at customer sites, above ground and underground conductors. Distribution circuits either consist of anchored or unanchored components.

Finally, loads of power systems are divided into *industrial*, *commercial* and *residential*.

Industrial loads are served directly from the high voltage transmission system or medium voltage distribution system. Commercial and residential loads consist largely of lighting, heating and cooling.

Loads are independent of frequency and consume negligibly small reactive power. The real power of loads is expressed in terms of kilowatts (kW) or megawatts (MW).

The magnitude of load varies throughout the day and power must be available to consumers on demand. The greatest value of load during a 24-hr period is called *peak demand*. Smaller peaking generators may be commissioned to meet the peak load that occurs for only a few hours. In order to assess the usefulness of the generating plant the load factor is defined, which is the ratio of average load over a designated period of time to the peak load occurring in that period. Load factors may be given for a day, a month or a year.

### 6.2 SYSTEMIC VULNERABILITY METHODOLOGY AND SOFTWARE IMPLEMENTATION

#### 6.2.1 Systemic vulnerability methodology and performance indicators

The analysis of an EPN in a seismically active environment can be carried out, as for other lifeline systems, at two different levels. The first basic one focuses on connectivity only and can only lead to a binary statement on whether any given node is connected with another node, specifically a source node, through the network. This level of analysis is particularly inadequate for a system such as the EPN since the tolerance on the amount and quality, in terms of voltage and frequency, of the power fed to any demand node for maintaining serviceability is very low. The actual power flow in the node must be determined to make any meaningful statement on the satisfaction of the power demand at the node, not just its state.
of continued connectivity. The latter is an intrinsically systemic problem since it depends on the determination of the flows on the entire (damaged) network. Further, before being able to evaluate flows it is necessary to determine what is the EPN portion still up and running after an event. This does not simply mean what components are damaged since damage to components has non-local consequences. Indeed, damage to the components of a substation can lead to a short-circuit that may or may not propagate further away from that substation to adjacent others, generating in extreme cases very large black-outs. Hence, power flow analysis follows the analysis of short-circuit propagation, in which circuit breakers are active components playing a key role in arresting the short-circuit spreading. This is the modeling approach adopted within the SYNER-G general methodology. Moreover, the substations are not modeled as vulnerable points, characterized by an assigned fragility function: their full internal logic is modeled, to account for partial functioning (continued service with reduced power flow) (see SYNER-G report D5.2, Pinto et al. 2011a). The eleven typologies of micro-components composing the load substations are the only elements in the network that are considered vulnerable. For such elements, fragility functions of peak ground acceleration (PGA) are available and reported in D3.3 (Pinto et al. 2010).

The quantitative measure of the EPN performance under seismic hazard is given by Performance Indicators (PIs), that 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”). A detailed discussion on performance indicators adopted in the SYNER-G general methodology is included in SYNER-G report D2.3 (Pinto et al. 2011b). In the following is only reported for reference a list of those computed in this application.

**System-level PIs**

- **Connectivity Loss**, or CL [deterministic, connectivity modeling] (Poljanšek et al. 2011). This index, whose definition is based on the concept of connectivity, for a generic system measures the average reduction in the ability of sinks to receive flow from sources:

\[
CL = 1 - \left\langle \frac{N'_i}{N_0} \right\rangle, \tag{6.1}
\]

where \( \left\langle \right\rangle \) denotes averaging over all sink vertices, while \( N'_i \) and \( N_0 \) are the number of sources connected to the \( i \)-th sink in the seismically damaged network and in non-seismic conditions, respectively. With reference to an EPN, sinks are load buses and sources are power plants.

- **Power Loss**, or PL [deterministic, connectivity modeling] (Poljanšek et al. 2011). This index upgrades the connectivity loss with the size of the power plants (in MW) to which sink vertices are still connected to:

\[
PL = 1 - \left\langle \frac{P'_i}{P'_0} \right\rangle, \tag{6.2}
\]

where \( P'_i \) and \( P'_0 \) are the sum of the real power of all the power plants connected to the \( i \)-th load bus in the seismically damaged network and in non-seismic conditions, respectively. PL can be seen as a weighted CL. For the case study in exam, PL yields the same values as CL, since all power plants generate the same power.
System Serviceability Index, or SSI [deterministic, capacitive modeling] (Vanzi, 1995). This index is defined as the ratio of the sum of the real power delivered from load buses after an earthquake, to that before the earthquake:

$$SSI = \frac{\sum_{i=1}^{N_o} P_{i,0} \cdot (1 - R_i) \cdot w_i \cdot 100}{\sum_{i=1}^{N_o} P_{i,0}}$$

where $P_{i,0}$ is the real power delivered from the $i$-th load bus in non-seismic conditions, i.e., the demand. In order to compute the eventually reduced power delivered in seismic conditions, two factors are considered. The first one, $R_i = \frac{V_{i,s} - V_{i,0}}{V_{i,0}}$, with $V_{i,s}$ and $V_{i,0}$ the voltage magnitudes in seismic and non-seismic conditions, is the percent reduction of voltage in the $i$-th load bus and if $V_{i,s} < V_{i,0}$ one has $1 - R_i = VR_i$ ($VR_i$ is introduced below). The second factor, $w_i$, is a weight function accounting for the small tolerance on voltage reduction: in particular, its value is 1 for $R_i \leq 10\%$ and 0 otherwise. The SSI index varies between 0 and 100, assuming the value 0 when there is no solution for the power-flow analysis and 1 when the EPN remains undamaged after the earthquake.

The above definition assumes that the demand remains fixed before and after the earthquake, since the index looks only at a single system, without considering the interactions of the EPN with the other infrastructure systems.

Moving average $\mu$ and moving standard deviation $\sigma$ of CL, PL and SSI [probabilistic, connectivity/capacitive modeling]. These parameters represent the evolution of the expected value and the standard deviation of the PIs during the simulation, until the current run.

Mean Annual Frequency (MAF) of exceedance of CL, PL and SSI [probabilistic, connectivity/capacitive modeling]. The MAF of the generic performance measure $Y$ exceeding threshold value $y$ is computed as:

$$\lambda_Y(y) = \sum_i \lambda_{0,i} G_{y,i}(y | i) = \sum_i p_i G_{y,i}(y | i) = \lambda_0 G_y(y)$$

by post-processing of the vector of sampled values of $Y$ to first obtain the complementary (experimental) distribution function $G_0(y)$. Then this distribution is multiplied by the MAF of all earthquakes in the region, $\lambda_0 = \sum_i \lambda_{0,i}$. The probability $p_i = \frac{\lambda_{0,i}}{\lambda_0}$ that, given an earthquake, it occurs on source $i$ is respected in the complementary distribution $G_0(y)$ where results come from events sampled in the correct proportion among the different sources.

Component-level PIs

Voltage Ratio or VR [deterministic, capacitive modeling]. For each bus inside the substations, this index is defined as the ratio of the voltage magnitude in the seismically damaged network to the reference value for non-seismic, normal conditions:
\[ VR_i = \frac{V_{i,a}}{V_{i,0}} \] (6.5)

The voltage computation requires a power-flow analysis on the network. Hence this index expresses a functional consequence in the \( i \)-th component of the physical damage to all system components. When interactions with other systems are modeled, \( VR \) expresses the functional consequence in the \( i \)-th component of the physical damage to components of all the interacting systems, i.e., it is the value of the index that changes due to the inter- and intra-dependencies, not its definition.

6.2.2 Software implementation

As addressed in SYNER-G report D2.1 (Franchin et al. 2011), the object-oriented paradigm (OOP) has been adopted for the purpose of modeling the Infrastructure and the seismic hazard acting upon it. Within the OOP, in abstract terms, the problem is described as a set of objects, characterized in terms of attributes (or properties) and methods, that interact with each other. Objects are instances (concrete realizations) of classes (abstract models, or templates for all objects with the same set of properties and methods).

The SYNER-G prototype software includes an object-oriented representation of a subset of all the systems in the taxonomy, among which is the electric power network. In the following are reported the properties and methods of the EPN class and its subclasses.

**The EPN class**

![Fig. 6.2 Class diagram for the EPN class](image)

Fig. 6.2 illustrates the EPN class diagram. In the software, the EPN is modeled as an undirected graph, i.e., a graph in which flow can occur in both directions on all. For this
reason, the EPN class is considered as a subclass of the *Undirected* abstract class, that in its turn is a subclass of the *Network* abstract class.

The electric power network is made up of nodes and edges/lines connecting them. As a consequence, the EPN class is the composition of *EPNedge* and *EPNnode* classes, that are both abstract. The first one is the generalization of the OverheadLine and UndergroundLine classes, while the second one is the generalization of the SlackBus, PVGenerator and *LoadBus* classes. The latter is the generalization of the TransformationDistribution and Distribution classes, both of which are composed of the *Component* abstract class. This latter class is the generalization of eleven classes, one for each micro-component composing the substations.

The following is the list of properties of the EPN class, with the names following the naming convention adopted for variables in developing the prototype software, whereby multi-word names have no blank spaces in between words and the latter are separated by capitalizing the initial letter of each word. The list is split into five parts:

*List of pointers*

- **parent**: this is a pointer to the parent object which, in this case, is the Infrastructure (the object from the Infrastructure class)
- **overheadLine**: pointers to the overhead transmission lines in the system, objects from the OverheadLine class (underground lines are not yet included in the model)
- **slack**: pointer to the slack bus, one object from the SlackBus class
- **generator**: pointers to all power generators (excluding the slack bus) in the system, objects from the PVGenerator class
- **transfdistr**: pointers to all transformation/distribution substations in the system, objects from the TransformationDistribution class
- **distribution**: pointers to all distribution substations in the system, objects from the Distribution class

*Electric Power Network global properties*

- **nEdges**: number of transmission lines in the EPN
- **nNodes**: number of buses in the EPN
- **edges**: connectivity matrix of the EPN listing the start and end nodes of each line
- **admittanceMatrix**: admittance matrix of the EPN, containing the self and mutual bus admittances, used in power flow evaluation
- **capacityPerCapita**: required average power per inhabitant, for the region of interest
- **vulnSites**: list of vulnerable sites (components) of the EPN, containing their location and IM type(s)
- **baseV**: reference voltage to switch to per-unit system (a way of normalizing quantities appearing in the power flow equations in order to obtain comparable values and improve convergence of the Newton solution strategy, see D5.2, Pinto et al. 2011a)
o **baseP**: reference power to switch to per-unit system
o **baseY**: reference admittance to switch to per-unit system
o **ULweight**: influence of EPN in the computation of utility loss (UL) in buildings (if present); the sum of ULweight values of the utility networks present in the Infrastructure must be 1. This is an important parameter in the model for the evaluation of the buildings habitability and hence the demand on the shelter model (see D2.1, Franchin et al. 2011)

o **adjacencyMatrix**

o **incidenceMatrix**

o **incidenceList**

o **deadEnds**: list of network dead ends

o **articPTS**: list of network **articulation points** (a graph-theoretic notion: nodes whose removal increases the number of connected sub-networks)

o **bridges**: list of **network bridges** (a graph-theoretic notion: edges whose removal increases the number of connected sub-networks)

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**Line and bus (node) properties** (many of these properties have counterparts in the **EPNedge** and **EPNnode** classes. Those in this class are vectors collecting values that are also stored individually within each node and edge object)

o **edgeVs30**: Vs30 value at the lines’ centroid

o **edgeVoltage**: nominal voltage of lines

o **edgeElectricProp**: electric properties of lines, i.e., resistance, reactance and susceptance, in units consistent with voltage and power units

o **edgeVoltageRatio**: ratio of voltages at the two ends of lines (different from 1 for lines with transformer)

o **edgeIsVulnerable**: flag indicating if the generic line is considered vulnerable or not

o **edgeCentroidPosition**

o **edgeType**: lines’ typology, overhead or underground

o **edgeIMType**: intensity measure used in the fragility of the edge

o **edgeSiteClass**: site class at the edge centroid site according to the amplification method to be used

o **edgeDepth2GW**: depth of the groundwater at the edge centroid site

o **edgeLiqSusClass**: liquefaction susceptibility of the edge centroid site

o **edgeLandSusClass**: landsliding susceptibility of the edge centroid site

o **edgeYieldAcc**: yielding or critical acceleration for landsliding at the edge centroid site

o **nodePosition**

o **nodeAltitude**
- **busBC**: buses boundary conditions (voltage magnitude and phase for the slack bus, voltage magnitude and real power for generators, real and reactive power for load buses)
- **nodeType**: typology (slack, generator, transformation/distribution or distribution) of buses
- **nodeVs30**
- **nodeIsVulnerable**: flag indicating if the generic node is considered vulnerable or not
- **nodeIMType**: intensity measure used in the fragility of the node (or the elements composing a station)
- **nodeSiteClass**: site class at the node sites according to the site amplification method to be used (valid for all *a posteriori* amplification methods, see Section 6.3.2)

**Properties that record the state of the EPN for each event**

- **states**: \( n_E \times 1 \) collection of properties that describe the current state for each of the \( n_E \) events
  - **Ybus**: current admittance matrix
  - **X0**: initial guess vector for power flow
  - **P**: current vector of real power at buses
  - **Q**: current vector of reactive power at buses
  - **loss**: current vector of lines complex power losses
  - **totalLossP**: total real power loss
  - **totalLossQ**: total reactive power loss
  - **numSources**: number of power plants connected to load buses
  - **numSourcesP**: sum of real power of power plants connected to load buses
  - **CL**: Connectivity Loss, system-level performance indicator
  - **PL**: Connectivity Loss, system-level performance indicator
  - **SSI**: System Serviceability Index, system-level performance indicator

**Properties that store the global performance of the EPN at the end of simulation**

- **MAF**: Mean Annual Frequency of exceedance values for the considered system-level PIs

The following is the list of the methods of the EPN class (some of these are briefly explained):

- **anySDFS**: performs the Depth First Search algorithm, to know which vertices can be reached by a path starting from any source
- **buildAdmittance**: builds the network admittance matrix
- **buildInitialEstimate**: builds an initial guess vector for the Newton-Raphson algorithm.
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- **checkIsolatedBuses**: finds and delete buses that are isolated from the slack bus
- **computeDemand**: determines the required real power at all load buses in which the real power is set to 0 in the textual input. The computation for the generic load bus is based on the user-specified average power per inhabitant and the population of its reference cells, if any, i.e., the cells fed by the node itself
- **computeLineCurrFlowLosses**: retrieves the lines current, power flow and power loss, as well as the slack bus real and reactive power and the generators reactive power
- **computePerformanceIndicator
- **connectedNodes
- **defineStatCompState**: assigns a damage state to all components of a substation
- **deleteBuses**: deletes from the network broken buses
- **detectArticulationPoints
- **detectBridges
- **edges2Adjacency**: perform corresponding transformation
- **edges2IncidenceList**: perform corresponding transformation
- **edges2IncidenceMatrix**: perform corresponding transformation
- **findDeadEnds
- **isConnected**: determines whether a path exists between any two nodes in an undirected graph
- **minPath**: finds the minimum path between a pair of nodes
- **noSolutionFound**: assigns zero values to all electrical quantities, when no power flow solution is found, due to damage of the network
- **powerFlow**: performs the computation of voltage and power in all stations, as well as the current, power and power loss in all transmission lines, in both seismic and non-seismic conditions. This method calls the buildInitialEstimate method. If a solution is found for the stations voltages, then the computeLineCurrFlowLosses method is called, otherwise the noSolutionFound sets all quantities to zero for the current event
- **retrieveLandSusEdges
- **retrieveLiqSusEdges
- **retrieveSiteClassEdges
- **retrieveSiteClassNodes
- **retrieveVs30edges
- **retrieveVs30nodes
- **retrieveYieldAccEdges
- **spreadShortCircuitsInEPN
- **listOfEdges
o **switchToPhysicalUnits**: switch back to the physical units of voltage, power and admittance, in case the user chooses to work with the per-unit system

**The EPNedge class and subclasses**

The following is the list of properties of the *EPNedge* abstract class. These properties are common to the two subclasses of this class.

- **parent**: this is a pointer to the parent object which is in this case the electric power network (the object from the EPN class)
- **connectivity**: start and end node of the edge
- **centroid**: edge centroid location
- **L**: edge length
- **Vs30**: Vs30 at edge centroid
- **Voltage**
- **voltageRatio**
- **resistance**: line resistance
- **reactance**: line reactance
- **susceptance**: line susceptance
- **longAdmittance**: line longitudinal admittance
- **transAdmittance**: line transversal admittance
- **isVulnerable**
- **IMType**
- **states**: \( n_E \times 1 \) collection of properties that describe the current state for each of the \( n_E \) events
  - **I**: line current
  - **invI**: line inverse current
  - **flow**: line power flow
  - **invFlow**: line inverse power flow
  - **loss**: line complex power loss
  - **shortCircuitOut**: flag indicating if a short circuit spreads over the network starting from the considered line
  - **lineDown**: flag indicating if the considered line is out of service

The *EPNedge* abstract class and its subclasses do not have any methods (only the object constructor for the concrete subclasses).

**The EPNnode class and subclasses**

The following is the list of properties of the *EPNnode* abstract class. These properties are common to all subclasses of this class.

- **parent**: this is a pointer to the parent object which is in this case the electric power network (the object from the EPN class)
- position: node location
- altitude: node altitude
- Vs30: Vs30 at node
- Type
- BC
- isVulnerable
- IMType
- siteClass
- states: $n_E \times 1$ collection of properties that describe the current state for each of the $n_E$ events. For the slack bus and generators, the state only indicates the output of the power flow analysis, while for load buses the properties are:
  - phi: voltage phase resulting from power flow (same property for the second bus, in case the station is of transformation/distribution type)
  - V: voltage magnitude resulting from power flow (same property for the second bus, in case the station is of transformation/distribution type)
  - primaryIM: primary intensity measure at node site, as interpolated from the regular grid points
  - localIMs: secondary or local intensity measures, correlated to the primary IM
  - brokenComp: list of flags indicating if the generic component is broken
  - busDown: flag indicating if the considered bus is out of service (same property for the second bus, in case the station is of transformation/distribution type)
  - isolatedBus: flag indicating if the considered bus is isolated from the slack bus (same property for the second bus, in case the station is of transformation/distribution type)
  - shortCircuitOut: flag indicating if a short circuit spreads over the network starting from the considered station
  - shortCircuitIn: flag indicating if a short circuit, spread over the network, enters the considered station
  - VR: voltage ratio, ratio of voltage in seismic conditions to voltage in reference condition

The abstract subclass LoadBus has two further properties, i.e., component (list of pointers to components composing the stations) and refCells (cells fed by the station). The TransformationDistribution and Distribution classes have further properties indicating the correspondent bus or buses ID numbers and the pointers to lines entering or exiting from the station.
The $EPNode$ abstract class has no methods, while the $LoadBus$ abstract class has three methods, present in all its subclasses (TransformationDistribution and Distribution classes).

- createComponents
- spreadShortCircuitsInStation
- checkStationDamage

The $checkStationDamage$ method is called inside the $spreadShortCircuitsInStation$ method to eventually delete the transmission lines affected by short circuits.

The TransformationDistribution and Distribution classes are composed of the $Component$ abstract class, which is the generalisation of eleven classes, one for each micro-component composing the substations. In particular, these classes are:

- BarSupport
- Box
- CircuitBreaker
- CoilSupport
- CurrentTransformer
- VoltageTransformer
- HorDisconnectSwitch
- VertDisconnectSwitch
- LightningArrester
- PowerSupplyToProtectionSystem
- Transformer

The following is the list of properties of the $Component$ abstract class. These properties are common to all subclasses of this class.

- parent: this is a pointer to the parent object which is in this case one of the network stations
- mean: log-mean, i.e., the first parameter of the lognormal fragility curve
- beta: log-std, i.e., the second parameter of the lognormal fragility curve
- fragility: vector of fragility curve values
- states: $n_E \times 1$ collection of properties that describe the current state for each of the $n_E$ events. For all component is present the flag broken. Only for circuit breakers, also the flags open and passive are present.

The $Component$ abstract class has no methods.
6.3 THE CASE STUDY

6.3.1 General description

The power network of Sicily, one of the Italian major islands, has been chosen as the case study. Significant earthquakes have not affected the island in recent times; hence the study is more a real scale application to test the capabilities of the SYNER-G methodology and prototype software rather than a validation study.

The available data about the system topology and characteristics are those provided by the former Italian State Electricity Board, ENEL (the network is now run under concession by another subject called TERNA, which manages only the transmission/distribution infrastructure while generation is distributed between a number of operators that compete in a recently freed market for energy). Hence, data may not be up to the date of this report.

6.3.2 Seismic hazard

The seismic hazard is modeled through 18 faults taken from the Italian DISS (Database of Individual Seismogenic Sources) database, employing the truncated Gutenberg & Richter recurrence model for the source activity (Fig. 6.3).

Within the DISS source model, also used in the European SHARE fault database, the fault surface does not correspond to a simple rectangle (seismogenic area), but is described as a more complex polygon that can change strike according to the trace. The current fault typology used within the SYNER-G model and the prototype software implementation for shallow faults in Europe (except the Aegean, Calabrian and Cypriot subduction interfaces) is simpleFaultGeometry. The fault is described by a trace, a dip and an upper and lower depth (the dip direction is always 90° clockwise from the azimuth to the last point on the trace from the first point of the trace). The rendering of an evenly-spaced discrete mesh over the fault surface is done using an adaption of the algorithm of Mark Stirling, which is what is
Currently implemented in OpenSHA (Open Source Seismic Hazard Analysis [http://www.opensha.org/](http://www.opensha.org/)). The fault source, as it is represented in this fashion, is equivalent to a composite source (see Weatherhill et al. 2011).

The ground motion prediction equation (GMPE) employed in this application is that by Akkar and Bommer (2010).

Different amplification methods are available: Eurocode 8, NEHRP, Choi&Stewart, context-specific. Such methods amplify the shaking intensity measure (IM) at vulnerable sites \textit{a posteriori}, i.e., after the ground motion calculation stage. It can also be used within-GMPE amplification method, using the Vs30 values for site classification. However, no soil classification data are available in the employed data set and, hence, IM values (i.e., PGA) are computed on rock.

Fig. 6.4 shows a shake map in terms of primary IM (in this case PGA) computed at points of a regular grid, for a scenario M=5.4 event. The primary IM is then retrieved at vulnerable sites by distance-based interpolation and finally the local IM (if not coinciding with primary) is sampled conditionally on primary IM. A detailed description of the entire hazard model adopted in the methodology and hence implemented in the SYNER-G prototype software can be found in Cavalieri et al. (2012) and SYNER-G reports D2.1 (Franchin et al. 2011) and D2.13 (Weatherhill et al. 2011).

![Fig. 6.4 Shake map in terms of PGA at grid points, for a scenario M=5.4 event](image)

### 6.3.3 System topology and characteristics

The island’s power network is composed of 181 nodes and 220 transmission lines. The nodes, i.e., the buses, are subdivided into 175 demand or load nodes and 6 supply nodes, 5 of which are power plants and 1 is the balance node (or slack bus). The load nodes (two for transmission/distribution and one for distribution substations) deliver power to users. The total number of municipalities served by the network is 390.
The balance node, generally coinciding with the generation node providing the highest power, is introduced in the adopted power flow formulation (see D5.2 Pinto et al. 2011a) since power losses in the network are unknown before solving the power flow equations. Its function is to provide the power balance between the power ingoing at generation nodes and the power outgoing from load buses, plus the power losses. Fig. 6.5 shows the position of municipalities and network nodes on the island. All transmission lines are overhead lines and not considered as vulnerable elements. They are classified into high (HV), medium (MV) and low voltage (LV) lines (Fig. 6.6). The EPN is modeled as an undirected un-weighted graph.
6.3.4 Description of the input

The MATLAB environment provides through the function `xlsread` the capability of importing data organised within an Excel workbook. The latter was chosen as the format of the input file for the prototype software. Input is prepared as a workbook within which, in general, each sheet correspond to a different system in the SYNER-G taxonomy.

The first two cells in the `epn` sheet specify the number of lines (sides) and of nodes, 220 and 181, respectively. The installed capacity per capita is needed to compute the power demand requested by buildings: for this application, in which the building system is not present in the Infrastructure, the power demand data are provided by ENEL. The base voltage and power are reference values that serve the purpose of working with the per-unit system, if desired. The UL (Utility Loss) weight is the importance the user wants to give to EPN in the computation of total utility loss (see D2.1, Franchin et al. 2011).

The next rows, after the `nodes` keyword, specify in a standardised way (similar for all network/line-like systems) the nodes of the system. In particular the information to be provided for each node is in the order: localisation, site properties, functional and related to seismic damageability. Localisation is given in terms of latitude and longitude in degrees and altitude above sea level in meters. The site properties are specified in terms of average shear wave velocity Vs30. It can be noted that Vs30 is set to a very high value (1000 m/s) for all nodes, meaning rock sites; in fact, for values higher than 750 m/s the software considers the sites to be on rock and does not amplify their local IM. Functional information for the stations of an EPN is the type of node (balance, generator, distribution or transformation/distribution) and the node boundary conditions (see D5.2 Pinto et al. 2011a).

The next two columns specify whether the node is vulnerable, and in this case, the IMs to be input to the corresponding fragility model. The last column reports the site class, needed for post hoc amplification methods.

The next part of the `epn` sheet, after the `sides` keyword, specifies in a standardised way (similar for all network/line-like systems) the sides/lines of the system. Lines with and without transformer are grouped together for convenience. The first two columns indicate the line connectivity (start and end nodes). The site properties are specified in terms of average shear wave velocity Vs30. Functional information includes the line typology (overhead or underground), the line voltage (set to 0 for lines with transformer), the line electric properties (resistance, reactance, susceptance) and the voltage ratio (set to 1 for lines without transformer).

As for the nodes, two columns specify whether the edge is vulnerable, and in this case, which is the IM(s) to be input to the corresponding fragility model.

6.4 RESULTS

Three types of simulations have been carried out: a plain Monte Carlo (MCS) and two improved simulations enhanced with variance reduction techniques, i.e., Importance Sampling (ISS) and Importance Sampling with k-means clustering (ISS-KM). The reader can refer to SYNER-G report D2.1 (Franchin et al. 2011) for an exhaustive description of such simulation schemes.
The analysis results as obtained from a plain MCS of 20,000 runs are presented in the following figures. The chosen number of runs showed to yield stable estimates for all considered PIs.

Fig. 6.7 Moving average $\mu$, $\mu+\sigma$ and $\mu-\sigma$ curves for CL (left) and SSI (right)

Fig. 6.7 shows the moving average $\mu$ curves for CL (left) and SSI (right), as well as the $\mu+\sigma$ and $\mu-\sigma$ curves for the two PIs. The minimum sample size is strongly dependent on the chosen PI; in fact, SSI stabilises with less than 1,000 runs, whereas CL requires a much larger number of runs. The reason for this difference is that CL depends on the number of connected sources, rather than on the actual demand satisfaction at load buses. The number of connected sources is a more variable quantity, being affected by the uncertainty on short-circuit propagation, that causes a line to be turned off every time a short-circuit tries to spread outside one of the substations in the network.

Fig. 6.8 MAF curves for CL (left) and SSI (right)
Fig. 6.8 shows the MAF of exceedance curves for CL and SSI. The same feature highlighted by the moving average of the two PIs is observed by looking at the MAF curves. In fact, while the CL MAF presents a wide range of variation, SSI confirms to be a very stable indicator, with MAF values ranging in a small interval.

![Fig. 6.8 MAF curves for CL and SSI](image)

**Fig. 6.8 MAF of exceedance curves for CL and SSI**

Fig. 6.9 displays a contour map of the expected values of VR, averaged on the whole simulation for each demand node. It can be seen that the reduction in voltage due to seismically induced damage is less than the tolerated threshold of 10%, allowing the power demand delivery everywhere in the island, consistently with the very large value of SSI and very low value of CL.

With reference to some PIs, the results coming from MCS have been taken as the reference solution and compared with those obtained from the two variance reduction techniques, ISS (2,000 runs) and ISS-KM (200 runs). In particular, in Fig. 6.10 the comparison is relative to moving average curves of CL (left) and SSI (right), while in Fig. 6.11 it is referred to MAF curves of the same indicators.

The match of the curves is shown to be not very good in all cases, although the order of magnitude of values is comparable for $\mu$ curves and MAF curve of SSI. The effectiveness of ISS and ISS-KM was tested before with reference to some case studies (mostly buildings, not networks) and some particular PIs. The results of such tests were fully satisfactory. Therefore, the unsatisfactory match in this case hints at the fact that the match quality is strongly case-dependent and PI-dependent. Further studies on different systems analyzed with different approaches (connectivity/capacitive) are needed to draw guidelines for the use of such variance reduction techniques as a practical alternative to the cumbersome and time-consuming MCS.
6.5 CONCLUSIONS

The SYNER-G methodology has been applied to the power network of Sicily, one of the Italian major islands. Significant earthquakes have not affected the island in recent times; hence the study is more a real scale application to test the capabilities of the SYNER-G methodology and prototype software rather than a validation study against real data.

A capacitive study has been performed, with power flow analysis that follows the analysis of short-circuit propagation, in which circuit breakers are active components playing a key role in arresting the short-circuit spreading. The substations are not modeled as vulnerable points; in fact, their full internal logic is modeled, to account for partial functioning.
The electric power network and the seismic hazard acting upon it are modeled in the SYNER-G prototype software through the object-oriented paradigm, very efficient in allowing to avoid code duplication and in making the whole code modular.

Three types of simulation have been carried out (plain Monte Carlo (MCS), Importance Sampling (ISS) and Importance Sampling with k-means clustering (ISS-KM)), computing within each of them a number of performance indicators.

With reference to some PIs, the results coming from MCS have been taken as the reference solution and compared with those obtained from the two variance reduction techniques, ISS (2,000 runs) and ISS-KM (200 runs). The match of the curves is shown to be not very good in all cases, although the order of magnitude of values is comparable for $\mu$ curves and MAF curve of SSI.

Results coming from analyses carried out with reference to some case studies (mostly buildings, not networks) and some particular PIs, suggest that the efficacy of ISS and ISS-KM is strongly case-dependent and PI-dependent. Hence, further studies on different systems analyzed with different approaches (connectivity/capacitive) are needed to draw guidelines for the use of such variance reduction techniques as a practical alternative to the cumbersome and time-consuming MCS.
7 Application and validation study to a hospital facility in Italy

7.1 INTRODUCTION

The response of a regional health-care system is a function of the hospitals performance but also of other factors, among which the response of the road network is of primary importance.

The seismic performance of hospitals plays a key role in coping with the emergency. Hospitals are, typically, highly vulnerable facilities due to age of construction, types of equipment, occupancy rate, services provided, etc.; the seismic assessment of a (single) hospital facility is described in detail in SYNER-G reports D2.8 (Pinto et al. 2011a) and D3.10 (Pinto et al. 2011b). The hospital performance is expressed by the Hospital Treatment Capacity (HTC) index, which measures the residual surgical treatment capacity of the damaged facility.

The road network serves the purpose of connecting the hospitals in a regional health-care system: damages to the network may cause an increase in the distance to be covered because of interrupted links as well as a decrease in the transportation speed. Therefore, in the present study the road network is explicitly modeled and damages in vulnerable elements are evaluated and accounted for.

The large uncertainties affecting this complex problem require the use of a probabilistic approach. The seismic hazard is described by means of the distributed probabilistic model developed within the SYNER-G project (Franchin and Cavalieri 2012). The fragility curves for the HTC index, as well as the models to estimate the number of injured people to be hospitalized, derived in (Lupoi et al. 2008), are employed in the presented application.

With respect to the time-frame of a disaster (emergency, recovery, reconstruction), this study focuses on the short-term, emergency period after the seismic event (24/48 hours). The main goal is to forecast the expected impact in terms of: a) victims that cannot be hospitalized; b) hospitals that cannot provide medical care to the victims; c) city/villages that are not served by a functioning hospital within a “reasonable” distance.

7.2 SYSTEMIC VULNERABILITY METHODOLOGY AND SOFTWARE IMPLEMENTATION

7.2.1 Components and functioning of the system

The system under evaluation is composed of hospitals, area districts and a road network. The road network is deputed to connect districts and hospitals allowing the transportation of injured and sick people. The seismic event has both direct and indirect consequences on each component of the system. The response of the system depends not only on the performance of each component but also on their mutual interactions. The identification and
the evaluation of interactions is a difficult task, which unavoidably involves a number of assumptions and simplifications.

The consequences on a hospital facility are expressed in terms of the capability of providing medical services through the HTC index, which is affected not only by the physical damages to the building, but also by the performance of non-structural elements, by the response of the staff and by the effectiveness of the emergency procedure. In fact, the lack of medical staff and/or of adequate emergency procedures may severely impair the capability of providing medical services in emergency conditions.

Damages to the road network, and in particular to bridges, are also included. They affect the capability of transportation of the victims to hospitals, both by a reduction of the travel speed and by the closure to traffic of the collapsed bridges.

The number of victims is evaluated on the basis of demographic data by means of casualty models. The uncertainty in the estimation of victims is introduced in the analysis. Victims are evaluated per area districts, whose spatial extension may vary from a small neighbourhood to a whole town depending on the scale of the study and in the detail of the available information. Among all victims, a classification according to the severity of their condition is made by means of indications from epidemiologic studies (statistical data derived from previous events). The “severely injured” victims that need to be hospitalised are estimated and subdivided in two classes: those that need a surgical treatment, which form the Hospital Treatment Demand (HTD), and those that need a medical care and a bed. Victims that need to be hospitalised are transferred from the origin area districts to a hospital located in the region of study. The analysis is concluded either when all the patients are hospitalised or when all the hospitals in the region are saturated.

The system performance indicators are: a) the number of severely injured patients that will not be able to receive a surgical treatment or a bed (expressed in terms of mean annual frequency of exceedance or return period); b) the maximum travel time for hospitalisation; c) the risk that hospitals are not capable of providing the required surgical treatment (HTC/HTD) if an earthquake in the region occurs; d) the hospitalising rate and travel time disaggregated per area districts. The first two indicators measure the resilience of the regional hospitals network; the third indicator measures the adequateness of each hospital of the region to cope with the seismic emergency; the last indicators provide an indication of the quality of the medical services under emergency condition for each area district. The comparison of the hospitalisation travel time for different seismic retrofit/upgrade scenarios with the baseline distribution may give useful indications for the allocation of resources.

The components of the system and the “hospitalisation” model developed for this study are described in some more detail in the following sections.

The system described above can be viewed as a part of the SYNER-G general framework (e.g. Franchin and Cavalieri 2012), where an integrated approach for the assessment of the systemic seismic vulnerability and risk analysis of buildings, lifelines and infrastructures is developed. Damages to building aggregates are not accounted for in the present application; nevertheless, the general framework is comprehensive and can include them, as illustrated in (Cavalieri et al. 2012). It is therefore possible a detailed (and more accurate) estimation of the victims if (enough) data on the built area is known to the analyst.
7.2.2 Hospital Facility and Treatment Capacity

The seismic assessment of a hospital facility has been studied in detail in (Lupoi et al. 2008). The probabilistic approach developed for a single facility is here employed for the analysis at a regional scale. This section presents a brief summary of the procedure.

The hospital is described as a system made of three vulnerable components: human, organisational, physical. These components, of different nature, jointly contribute to provide an output: the medical services, which are standardised procedures established to guarantee an adequate treatment of patients.

The physical component is the facility where the medical services are delivered. It is made of structural elements and non-structural elements (architectural elements, basic contents and equipment). While the former are critical to preserve the life-safety of the building occupants, the latter are fundamental to preserve the hospital functionality. The human component is the hospital staff: doctors, nurses and in general whoever plays an active role in providing medical care. The organisational component is the set of standardised procedures established to ensure that medical services are delivered under adequate conditions.

The functioning of a hospital system is influenced by the external environment in many different ways: some factors act “directly” on the vulnerable components, e.g. site accessibility, soil conditions, etc., some others “indirectly”, e.g. social context, cultural background, economic pressures, standards, educational system, etc.

The performance assessment of a hospital is a task significantly more demanding than those of “simple” buildings or bridges. In fact, the contributions of all components and their mutual interactions have to be appropriately accounted for. From the consideration that the basic function of a hospital is accommodating the incoming flow of patients requiring hospitalisation, an ad-hoc performance measure has been developed: the HTC index, defined as the number of patients with serious injuries that the hospital can treat in one hour. The evaluation of the HTC index is affected by large uncertainties since it depends on several factors of difficult quantification, e.g. the medical conditions of the patients, the amount of resources available, etc.

A functional analysis of a hospital in emergency condition has been carried out, yielding the following major conclusions:

1. The identification of a sub-set of medical services that have to remain operative after the seismic event in order to guarantee the adequate treatment of patients and victims. These are classified as essential medical services;
2. The hospital treatment capacity, HTC, can be quantitatively measured by the number of functioning operating theatres, which represent the bottleneck of the health-care system after a mass-casualty event that produces trauma victims;
3. The influence of the organisational and human components on the HTC can be estimated only empirically on the basis of experts judgement;
4. The relationship between the damage state of the physical component and the HTC is (analytically) evaluated by means of engineering-based methods.

An expression has been developed for the HTC index:

\[
HTC = \alpha \cdot \beta \cdot \frac{Y_1 \cdot Y_2}{t_m}
\]  
(7.1)
where \( \alpha \) accounts for the efficiency of the emergency plan (organizational component), \( \beta \) accounts for the quality, training and preparation of the operators (human component) and \( \gamma_1 \) is the number of operating theatres which remain operative after the hazardous event. The factor \( \gamma_2 \) is a Boolean function equal to 1 if the system “survives” and to 0 otherwise, with the survival condition defined as:

- a) the operational performance level is met (after the seismic event) for the area where the essential medical services are delivered;
- b) the safeguard of human life performance level is met for all the other areas of the hospital, where the medical services other than the essential ones are provided.

Condition a) depends on the response of both structural and non-structural elements, while condition b) depends on the response of structural elements only.

The parameter \( t_m \) is the mean duration of a surgical operation (measured in hours).

The “essential medical services” typically are: Emergency department; Operating theatres; Intensive care unit; Diagnostics; Blood bank; Haemodialysis; Urology; Neonatology; Gynaecology/Obstetrics; Paediatrics; Laboratory; Pharmacy. The essential medical services have to stay operational after the event.

The vulnerability analysis of a hospital consists of the following actions:

- verifying that the hospital is provided of all the essential medical services, identifying their location in plan, defining the appropriate performance level for each area of the facility. It has to be considered that the hospital emergency layout (i.e., spatial location of the medical services) may differ from the everyday one;
- assessing the quality of the emergency plan, to provide an estimate of the coefficient \( \alpha \) in Equation (7.1). At the current state of development, this is done according to engineering judgment; typical values range from 0.5, for very poor emergency plans, up to 1 for excellent and complete ones. The lack of such a document certifies the inadequateness of the hospital in successfully coping with a seismic emergency, and the factor \( \alpha \) has to be taken equal to nil;
- verifying the existence of adequate resources and assessing the skill and the availability of operators to put in practice the emergency plan. This results in assigning a value to the \( \beta \) factor in (Equation 7.1). At the current state of development, this is done according to engineering judgment. Typical value may range from 0.5, for poorly trained and understaffed operators, up to 1 for well-trained and adequately-staffed ones;
- building up the fault-tree of the physical component to establish the relationship between the state of the vulnerable elements and the state of the system. The fault-tree analysis schematically depicts the vulnerable elements and their functional interrelationship. Generic fault-trees for typical sub-systems are provided in (Lupoi et al. 2008); they have to be appropriately “assembled” to build up the “system” fault-tree of the whole physical component. A generic fault-tree based on the distinction between essential and basic medical services is illustrated in Fig. 7.1. Since the fault-tree is hospital-dependent, it has to be customised on a case-by-case basis. A preliminary, thorough examination of the vulnerable elements is recommended in order to reduce as much as possible the branches of the system fault-tree;
• deriving the fragility curve for the HTC index, i.e., the relationship between the number of functioning operating theatres and the intensity of the ground motion. Among the two alternative approaches available in literature for deriving vulnerability curves, i.e., structure-specific vs category-based, the former has to be preferred since the peculiarity of each hospital does not allow the use of standardised curves: each hospital is a “prototype”. The techniques for deriving system-specific fragilities are based on detailed structural analyses. In addition, the employment of a probabilistic approach is an almost inevitable choice due to the large uncertainties characterising most of the quantities that contribute to the system response. Advances in structural reliability analysis supported by finite element platforms have made possible to systematise the analytical approach for establishing relations between earthquake characteristics and structural response/damage (Pinto et al. 2004). These methods allow a comprehensive description of the sources of uncertainty, the development and the update of vulnerability curves incorporating both empirical evidence based on observational data and analytical predictions. A relationship between structural response quantities and the ground motion intensity measure is derived by means of a reduced number of numerical analyses; the fragility curve is then evaluated by standard simulation techniques, e.g. Monte Carlo: if the system survives ($\gamma_2 = 1$), the hospital resources are measured in terms of the functioning operating theatres $\gamma_1$. 
Fig. 7.1 Example of a fault-tree for the physical component of a hospital
7.2.3 Casualty model and Hospital Treatment Demand

The number of casualties due to an earthquake event and of those who need a surgical treatment are estimated combining epidemiological studies and casualty models.

In current medical practice, a patient’s condition is classified by a colour tag according to the triage scheme: red tag for patients who require immediate care, yellow tag for those who require delayed care, green tag for those who need minimal care, black and blue tags for the deaths or for those who are not expected to survive despite any treatment.

Casualty models provide estimates of the “severely injured” people (i.e., those requiring to be hospitalised) and of the deaths: red-tag, yellow-tag and black/blue-tag patients. The lightly injured people (green-tagged) are ignored. The casualties expressed as percentage of the population can be evaluated by the expression (Coburn and Spence 1992) as simplified by Nuti and Vanzi 1998):

\[
C(I) = k (I - I_{min})^4
\]  
(7.2)

where \( I \) is the intensity measure of the seismic event, \( k \) and \( I_{min} \) are the model parameters which take into account both the vulnerability of the building stock and the occupancy rate. In the original model, the intensity measure is the Modified Mercalli Intensity (MMI); the relationship in (Wald et al. 1999) is employed to convert MMI into PGA. The model parameters have to be calibrated as function of the environmental conditions; the extent of damages to buildings has to be estimated by means of appropriate vulnerability functions. In the study of Nuti and Vanzi (1998), focusing on the hospital system of Regione Abruzzo, the model parameters have been taken equal to: \( k =0.00048 \) and \( I_{min} =7 \).

Casualty models have been developed by engineers from limited, anecdotal and historical data, with the scope of providing a rapid estimate of the earthquake impact on population for the purposes of response planning and mitigation. Since they are clearly affected by large uncertainties, an error term is included, \( \epsilon_{cas} \), having lognormal distribution, unit median and coefficient of variation equal to 0.3. The number of the victims, \( N_{r+y+bb} \), is then given by:

\[
N_{r+y+bb} = C(I) \epsilon_{cas} N_{pop}
\]  
(7.3)

where \( N_{pop} \) is the population in the area affected by the earthquake.

The Hospital Treatment Demand, \( HTD \), defined above as the number of people that require a surgical treatment, is a sub-set of the red-tag and yellow-tag patients:

\[
HTD = \zeta N_{r+y}
\]  
(7.4)

with \( N_{r+y} \) the number of red-tag plus yellow-tag patients and \( \zeta \) a factor whose value is typically in the range between 1/3 and 1/2. The actual value has to be defined on a case-by-case basis by expert opinion.

The proportion of “severely” injured people over all casualties is derived from epidemiological studies, i.e., the study of the patterns of disease and injury in human populations, which provides fundamental information of type and amount of resources needed to treat casualties. In fact, the types and numbers of casualties vary with the characteristics of the earthquake, the building stock in the struck area, the demography and also with the time of the day when the earthquake occurs. In epidemiology, the “medical severity” of a hazardous event is assessed by two severity indexes:
Application and validation study to a hospital facility in Italy

\[ S_1 = T_{red} \left( T_r + T_y + T_g \right) \]  \hspace{1cm} (7.5)

\[ S_2 = \left( T_r + T_y \right) / T_g \]  \hspace{1cm} (7.6)

where \( T_r \) is the percentage of red-tag patients, \( T_y \) the percentage of yellow-tag patients and so on. The index \( S_1 \) gives an indication of overall severity of the event (deaths over injured), while the index \( S_2 \) measures the severity of the injuries caused by the event (seriously injured over lightly injured). For the same number of casualties, the larger is the value of \( S_2 \), the greater is the amount of medical resources that are needed to treat the victims. Data from past earthquakes have shown that the value of \( S_1 \) is comprised between 0.1 and 0.5, while the one of \( S_2 \) between 0.15 and 0.6.

The estimate of \( N_{r+y} \) is obtained combining \( N_{r+y+bb} \), from Equation (7.3) with the severity indices \( S_1 \) and \( S_2 \) from Equation (7.5) and Equation (7.6). After some manipulations, the following expression is obtained:

\[ N_{r+y} = \left[ \frac{S_2}{S_1 + S_1 S_2 + S_2} \right] N_{r+y+bb} \]  \hspace{1cm} (7.7)

The final expression for HTD is:

\[ N_{r+y} = \xi \left[ \frac{S_2}{S_1 + S_1 S_2 + S_2} \right] C(I) \xi_{cas} N_{pop} \]  \hspace{1cm} (7.8)

7.2.4 Road Network

In this study the function of the Road Network is to allow the transportation of the injured to hospitals. The analysis is carried out in terms of pure connectivity, i.e., the traffic flows are not modeled. This is coherent with the time-frame of the study, limited to rescue operations in the aftermath of the seismic event. The interest is the identification of the portions of the network critical with respect to the continued connectivity of the network: damages to the vulnerable elements of the road network are evaluated and accounted for.

This approach requires a simple description of the network in terms of a graph; analysis tools are limited to basic graph theory results. The road network is represented as a graph consisting of \( n \) nodes or vertices, connected by \( n_a \) arcs, or links or edges. The relationship between nodes and arcs is described by the adjacency matrix \( B = [b_{ij}] \), which is a \( n \times n \) Boolean square matrix, whose terms are either 0, when no connection exists between nodes \( i \) and \( j \), or 1 when a connection exists.

The graph is directed (also known as digraph), which means that the existence of a link from nodes \( i \) to \( j \) does not imply the presence of a link between nodes \( j \) and \( i \) (e.g. some roads are one-way only); as a consequence, the adjacency matrix is not symmetric. When for every directed arc the opposite one exists, the graph is said to be symmetric, or non-directed or simply a graph. Two different types of connectivity are involved: strong and weak. The latter does not consider the edges directions, actually treating the network as non-directed. Of course, for non-directed graphs only the weak connectivity can be considered. In general, a graph is composed of one or more (strongly or weakly) connected components (i.e., groups of connected nodes).
Given a graph, a finite or infinite sequence of links such that the origin node of each arc coincides with the destination node of the previous one is called a path $P$. The order of the path is the number $n_p$ of links making up the path. A free-flow travel speed is assigned to each arch of the graph.

### 7.2.5 Transportation and Medical Treatment Model of the victims

Transportation is assumed to take place by private vehicles on the damaged road network. The selection of the hospital, made by users, is affected by both objective constraints and subjective choices. The closure of a road represents one of the former; the user “familiarity” with a specific facility is one of the latter. This section briefly addresses the proposed model for the transportation of casualties to the hospitals of the region of interest.

In Section 7.2.3 an expression has been derived for $HTD$, considered as a fraction of red-tag plus yellow-tag casualties. The complementary portion of casualties with respect to $N_{r+y}$ is made up of the injured (called $HTD$ in the following) that do not need a surgical treatment, but only a bed for medical care.

The implemented algorithm is iterative, since patients arrived at a hospital might not receive medical care if such hospital is severely damaged (not operative, $\gamma_2 = 0$) or has its capacity saturated, either in terms of available beds or of number of functioning operating theatres ($HTC$).

At the beginning of the first iteration, the availability of all the region hospitals is checked, both for $HTD$ (by counting the number of available beds) and for $HTD$ (verifying that the $HTC$ of the damaged hospitals is greater than zero). Unavailable facilities are excluded. Then, the estimated victims of all area districts (or Traffic Analysis Zones, TAZs) are moved to the hospital closest, in terms of minimum travel time computed on the damaged road network, from their area district. Once they reach their “first-choice” hospital, they are allocated based on their arrival time, i.e., following the “first-come, first-served” criterion. If the hospital capacity is reached, separately for the two types of victims, the not-allocated casualties are forced to move to the next closest hospital facility. The second and subsequent iterations are similar to the first one; the only difference stands in the fact that casualties are moved only between hospitals, since all of them left their origin area districts. The analysis is concluded either when all the casualties are hospitalised or when all the functioning hospitals in the region are saturated (all available beds are used or $HTC \leq HTD$, depending on the type of casualties).

In this model a possible choice could be to assume that the injured victims that do not need surgical treatment, i.e., $HTD$, can always receive medical assistance at the first operative hospital which they reach. This is coherent with the emergence procedures activated in the case of a natural disaster, where the number of medical treatments may be doubled with respect to standard, “every-day” condition (eventually by field hospitals). In the computation of the travel time to reach the hospital, an unreduced free-flow speed is assumed for highways, while a 50% reduction in speed is considered for the urban portions of the road network in order to account for the potential damage to buildings (and hence road blockage) and other possible random events.
7.2.6 Treatment of uncertainties and software implementation

The probabilistic assessment of the regional health-care system is carried out employing a standard simulation-based method. This approach is characterised by robustness; the computational efficiency may be enhanced by means of a number of variance reduction techniques, e.g. (Jayaram and Baker 2010).

The described system presents multiple input uncertainties. These range from those related to the regional seismic activity and the corresponding local intensity at each site, to those related to the physical damage state as a function of local intensity, to the uncertainty on the parameters (or even the form) of the fragility models employed.

Uncertainty on the seismic hazard is modeled through two models, the event model and the local intensity model (Franchin and Cavalieri 2012). The event model starts with a continuous variable \( M \) for the event magnitude, continues with a discrete random variable \( Z \) for the active zone, with as many states as the number of seismo-genetic zones, and ends with a random variable \( L \) for the epicentre location within the active source. Distributions vary according to the adopted sampling scheme, but that of \( Z \) is conditional on the sampled value of \( M \), and that of \( L \) is conditional on the sample zone \( Z \).

Local intensity measure (IM) at the sites of vulnerable components is described with a vector of IMs that are needed as an input to the corresponding fragility model. A scalar random field of a so-called “primary IM”, e.g. PGA, on rock (no amplification yet) is first sampled as a function of the sampled \( M \) and \( L \) on a regular grid covering the study region, employing a ground motion prediction equation (GMPE) with inter- and intra-event error terms \( \eta \) and \( \varepsilon \). In the application to follow the employed GMPE is that by Akkar and Bommer (2010). Intra-event residuals \( \varepsilon \) are modeled as a spatially correlated random field (Jayaram and Baker 2009) by means of an exponential auto-correlation function derived for Italian events and consistently with the Akkar and Bommer GMPE in (Esposito et al. 2010). The need for sampling on a regular grid first arises to avoid singularity problems in the covariance matrix of intra-event residuals, since sites usually occur in clusters with very similar source-to-site distances. The primary IM is then interpolated to all sites and “secondary IMs” (all other components in the intensity vector at a site) are sampled from their distribution conditional on the primary IM value (postulating joint lognormality of the IMs, see e.g. Bazzurro and Cornell, 2002, and using inter-IM correlation values from Baker and Cornell, 2006). Where needed, intensities are amplified based on local soil conditions, with probabilistic amplification functions.

Uncertainty in the physical vulnerability of components is described by a set of lognormal fragility functions. The physical damage state of all components, \( D \), is sampled as a function of the input intensity measures. Once \( D \) is known, the functional analysis of each system can be carried out to determine its performance. At this stage physical interactions are also considered (such as, for instance, detour to reach hospitals from area districts due to the closure of damaged portions of roads).

The basic random variables typically involved in the derivation of fragility curves are the strength of materials, the amount of reinforcement in RC structures, the capacity models for structural and non-structural elements, etc. The derivation of fragility curves for the system components is out of the scope of the present study. The uncertainty in the estimation of the victims is described in section 7.2.3.
This typical simulation run is carried out as part of either a plain Monte Carlo simulation or a more effective importance sampling scheme.

For what concern software implementation, numerical analyses are carried out employing the SYNER-G prototype software, which is illustrated in Section 2.2 of the chapter devoted to Road Network. In fact, the seismic hazard and the road network classes are common to road network and regional health-care applications. The hospitalization iterative algorithm describe before has been implemented in the code.

### 7.3 THE EXAMPLE APPLICATION

#### 7.3.1 General description

A hypothetical region with an infrastructure (system of systems) composed of a road network (RDN) and a health care system (HCS) is shown in Fig. 7.2. The architecture of the RDN has been taken from the application example in Kang et al. (2008). Then, some modifications and additions have been made in this work to form an infrastructure that is subjected to a distributed seismic hazard and in which the RDN/HCS interaction is taken into account.

![Fig. 7.2 The hypothetical study area](image)

#### 7.3.2 System topology and characteristics

Given the illustrative character of the application, several simplifications are made. The transportation network connects eight towns by highways with twelve bridges. It is studied with a pure connectivity approach, i.e., no traffic flows are computed in the damaged network. For simplicity, it is assumed that no other roads aside from the highways exist between cities and that the bridges are the only vulnerable components, whose earthquake induced damage may cause paths to be disconnected.
As shown in Fig. 7.3, left, two bridge types are considered, single-bent and two-bent overpasses. Since only network connectivity is analysed, only one fragility curve is assigned to each type, expressing the conditional probability of attaining or exceeding the collapse limit state for a given value of $PGA$. In other words, a bridge is assumed to be in one of the following two states: collapse/survival.

The eight towns have populations ranging from 8,000 to 20,000 inhabitants, for a regional population equal to 105,000. Such towns are considered as traffic analysis zones (TAZs), whose centroids are taken as the RDN nodes. The HCS comprises three hospitals, located in towns [1, 5, 8] and having a total number of beds, a number of beds already occupied in the pre-seismic conditions and a number of available beds (see Table 7.1).

<table>
<thead>
<tr>
<th>Hospital # / TAZ #</th>
<th># total beds</th>
<th># occupied beds</th>
<th># available beds</th>
<th># surgical treatments per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 / 1</td>
<td>300</td>
<td>210</td>
<td>90</td>
<td>77</td>
</tr>
<tr>
<td>2 / 5</td>
<td>400</td>
<td>320</td>
<td>80</td>
<td>77</td>
</tr>
<tr>
<td>3 / 8</td>
<td>350</td>
<td>290</td>
<td>60</td>
<td>77</td>
</tr>
</tbody>
</table>

All hospitals are also characterised by a health treatment capacity, $HTC$, considered here as the number of surgical treatments per day, since it is assumed that casualties are allocated in hospitals within one day. The employed $HTC$ curves, shown in Fig. 7.3 (right), have been derived for the real case of an existing facility located in Lamezia Terme (Italy) (Lupoi et al. 2008). The hospital fault-tree is shown in Fig. 7.1; uncertainties in both structural and non-structural elements have been accounted. The factors $\alpha$ and $\beta$ in Equation (7.1) have been taken equal to 1 and 0.8, respectively, while the mean duration of a surgical treatment has been assumed equal to $t_m = 2$ hours. The mean and standard deviation of the $HTC$ index have been evaluated conditional on $PGA$ by means of a Monte Carlo simulation. The mean and mean minus/plus one std curves are assigned for this example to hospitals located in
TAZs 1, 5 and 8, respectively: such curves allow to compute the damaged or residual (post-seismic conditions) HTC for a given value of PGA.

The casualty model parameters $k$ and $l_{\text{min}}$ in Equation (7.2) have been set to 0.01 and 5, respectively; the severity indexes $S_1$ and $S_2$ in Equation (7.8) are taken equal to 0.154 and 0.625, respectively (FEMA 1999).

### 7.3.3 Seismic hazard

Fig. 7.2 also shows three seismo-genetic area sources that can generate events affecting the region, together with their corresponding activity parameters for the truncated Gutenberg-Richter recurrence law: mean annual rate of all events in the source $\lambda$, magnitude slope $\beta$, and lower and upper magnitude limits $M_L$ and $M_U$.

### 7.4 RESULTS

A plain Monte Carlo simulation with 10,000 runs is carried out to test the proposed methodology. The expected value of the total number of casualties, $N_{\text{r+y}}$, over the 10,000 runs is equal to 75 (0.07% of the regional population); among those, the expected HTD are 52, while the HTD are 23. Please note that these figures do not include deaths (blue and black tag) and lightly injured people (green tag).

The first indicator to measure the resilience of the regional health-care system is the number of victims that cannot receive the medical care. This is expressed in terms of Mean Annual Frequency (MAF) of exceedance (or, equivalently, of return period of the event which causes the exceeding of un-hospitalised victims). The corresponding curves for the HTD and HTD, normalised to the regional population, are shown in Fig. 7.4. For example, the return period of the event with the 0.1% of the regional population that cannot receive the (needed) surgical treatment (red curve) is 100 years.

![Fig. 7.4 MAF curves of normalised casualties (divided in two categories) that are not allocated in hospitals](image)

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A second indicator is the maximum hospitalisation travel time. The moving average \( \mu \) and moving standard deviation \( \sigma \) are computed at each simulation run. Corresponding curves of \( \mu \) and \( \mu \pm \sigma \) are shown in Fig. 7.5. For the investigated system, the expectation of the maximum hospitalisation time is 36 min. The mean of the indicator becomes stable after about 1,000 runs, and this justifies the adopted number of runs.

Fig. 7.5 Evolution of maximum travel time for hospitalisation

The resilience of the hospitals in the region is expressed by the probability of not being able to provide the required surgical treatments to victims if an earthquake strikes the region (i.e., the seismic risk), as shown by the bar plot in Fig. 7.6. The results are in agreement with the treatment capacity curves employed for hospitals and the assumed configuration of the study area, where the seismic sources are located in the western part. In fact, the distribution of the seismic risk reflects both the source to hospital-site distance (hospital in TAZ #5 is the closest) and the assumed vulnerability of the facilities in terms of HTC fragility curves (hospital in TAZ #5 has the lowest treatment capacity).

Fig. 7.6 \( P(HTD \geq HTC) \), for the three region hospitals.
7.5 CONCLUSIONS

A methodology for the seismic assessment of a regional health-care system is presented in this study applying the SYNER-G methodology and tools. The system is composed of hospitals, area districts and road network. The road network is deputed to connect districts and hospitals allowing the transportation of injured and sick people. To properly assess the response of the system, the vulnerability of the system components, i.e., hospitals and roads, as well as the interaction among them are accounted for. This represents a novelty of the proposed methodology with respect to common applications.

A probabilistic approach has been employed to model the large uncertainties that affect the problem. In particular, the hospitals capacity and bridges physical damage are represented by fragility curves. Uncertainties in the evaluation of the casualties are also introduced. A model for the hospitalization of the victims has been developed and implemented.

The capabilities of the proposed SYNER-G methodology have been tested by means of an example application to a hypothetical region. A Monte Carlo simulation has been carried out to analyze the system. Results are expressed in terms of un-hospitalized victims annual exceedance rate, hospitalization travel time and hospitals seismic risk. The information is useful for emergency managers and for authorities in planning the emergency operations and in developing mitigation strategies.
8 Application and validation study to the harbour of Thessaloniki

8.1 INTRODUCTION

For the assessment of the systemic vulnerability and performance of harbors, a general methodology and appropriate tools were developed for the simulation of port operations and the derivation of the system performance in case of earthquake events. The objective of the present study is to apply and test the methods and tools developed in SYNER-G using the port of Thessaloniki as a case study.

Following the methodological framework for the systemic analysis developed in SYNER-G, waterfront structures, cargo handling equipment, power supply system, roadway system and buildings are examined. The main Performance Indicator (PI) used is the total cargo/containers handled in a pre-defined time frame per terminal and for the whole port system. An important interdependency considered within SYNER-G is between the cargo handling equipment and EPN, in particular for the electric power supply to cranes. Road closures due to potential building collapses are also another important dependency.

For the seismic hazard input, five seismic zones with \( M_{\text{min}} = 5.5 \) and \( M_{\text{max}} = 7.5 \) are selected based on the results of SHARE European research project (Arvidsson et al. 2010). Appropriate fragility curves are applied for the vulnerability assessment of each element at risk. A Monte Carlo simulation (MCS) has been carried out (10,000 runs) which samples earthquake events based on the methods and tools developed in SYNER-G.

The description of the port systemic vulnerability methodology and software implementation is provided, along with the description of the system topology and characteristics and the input for the analysis and finally the results of the application. Selected Performance Indicators (PIs) are calculated based on the estimated damages and functionality losses of the different components. The overall performance of the port system is expressed through the moving average \( \mu \) and moving standard deviation \( \sigma \) (averaged over simulations), as well as the Mean Annual Frequency (MAF) of exceedance of the PIs. The average loss is defined based on the moving average graph. The earthquake event that corresponds to a return period of the PI equal to \( T_m = 500 \) years is identified and maps with the distribution of damages are produced for this event. The correlation of each component to the system PIs is estimated. This type of analysis is based on the results of each single event, and thus it preserves the information about system’s topology and its behavior in case of spatial correlated damages (related to single earthquakes). Thus, it allows identifying the most critical elements for the functionality of the port system (i.e., the damaged components that more closely control the performance of the harbor).

Several sources of uncertainties are inherent to the analysis, related among others to the seismic hazard and spatial correlation models, the fragility assessment or the functionality thresholds of each component. The epistemic uncertainty related to different fragility functions and functionality definitions is investigated by performing sensitivity analysis with the use of alternative fragility curves and functionality thresholds for the waterfront structures.
8.2 SYSTEMIC VULNERABILITY METHODOLOGY AND SOFTWARE IMPLEMENTATION

8.2.1 Systemic vulnerability methodology and performance indicators

For the assessment of the systemic vulnerability of harbors, it is essential to simulate port operations. Since most of the dry cargo in modern ports is containerized, it has been decided in this application to focus on the operation of container handling. However, bulk cargo is also important from the viewpoint of risk management on economic activities such as industrial and insurance market. Given that, in the aftermath of significant natural disasters such an earthquake event, port facilities may also be one of “gates” for delivering the necessary assistance to the city, the importance of this analysis may also go beyond the strictly economic consequences. The passenger movement is also an important element to monitor a depression and recovery process of port function. Nevertheless, there is not enough data on passenger movement to assess the vulnerability in past earthquake events. From this point of view, it would be difficult to develop simulation models.

Based on this, container and bulk cargo movements of ports are simulated. The assumption of discrete type of cargo handling (container or bulk cargo) per terminal is made. The elements studied include piers, berths, waterfront and container/cargo handling equipment (cranes). Waterfronts and cranes are the physical components of the harbor. Piers and berths are structural (functional) elements. Several berths are composing a pier. Each berth is a part of a waterfront designed to serve one ship, and it consists of a portion of a waterfront served by one or more cranes. The berth length is estimated based on the pier’s operational depth. To quantify the capacity of each berth, each crane capacity (lifts per hour / tons per hour) is considered in the evaluation. The main Performance Indicator (PI) used is the total cargo/containers handled in a pre-defined time frame per terminal and for the whole port system.

An important interdependency considered within SYNER-G is between the cargo handling equipment and Electric Power Network (EPN), in particular for the electric power supply to cranes. If a crane node is not fed by the reference EPN node (electric supply station) with power and the crane does not have a back-up power supply, then the crane itself is considered out of service. Road closures due to potential building collapses are also another important dependency. In this case, the delivering process of cargo/containers from the terminals to the port gates could be hampered.

The functionality of the harbor is assessed through several system-level Performance Indicators (PIs), as evaluated starting from the effects of seismic events (Fig. 8.1). The general outline of the method is the following:

i. A set of seismic events sampled from the seismic hazard is defined.

ii. For each event defined in point (i):
   a. The fields for intensity measures within the harbor area are sampled.
   b. For all components, physical damages are sampled from their probability of occurrence, as assessed through fragility curves and the modeled intensity measures (point ii,a). In case of components sensitive to both ground shaking (PGA, PSA) and ground failure (PGD), like cranes, multiple IMs and damage
probabilities are estimated in parallel, and the results are combined through a Fault Tree Analysis (OR gate).

c. Based on the sampled physical damages for each event (point ii,b), the functionality state of each component is assessed, taking also into account system inter- and intra-dependencies.

d. For all systems, the PIs are evaluated based on functionality states of each component (point ii,c) and the systemic analysis. The “moving average” (average over all simulated events) is then computed.

iii. The results of the simulation are estimated. In particular:

a. The mean annual frequency of exceedance (MAF) for all PIs, based on the annual rates of seismic events (point i) and the evaluated PIs (point ii,d).

b. The rates of functionality (or damage) for each component, based on the results of points ii,c (or ii,b).

c. The correlation between functionality state (or damages) and PIs, based on the results of points ii,c (or ii,b) and ii,d.

d. Damages, functionality state and PIs are defined for a specific event (through the MAF curve) corresponding to predefined return periods (point iii,a).

The set of events defined in point (i) must be large enough to obtain stable results. During the simulation, the process of convergence toward stable results is visually checked from the “moving average” of each PI (point ii,d).

The diagram illustrates the functionality simulation of port facilities.

In the followings, the PIs selected for the harbor system and used in this application are described.

8.2.2 Container terminals

1. Terminal

The terminal performance is measured in terms of:

\[ \text{TCoH} = \text{total number of containers handled (loaded and unloaded) per DAY, in Twenty-foot Equivalent Units (TEU)} \]
For the harbor, the sum of the PIs relative to all container terminals is considered.

*Initial input data* include:

- the terminal considered,
- the number and location of piers,
- the operational depth of piers,
- the Vs30 at each pier,
- the location and pier of the cranes,
- the electric power demand EPNnode connected with each crane,
- the type of each crane (anchored or not),
- the presence/absence of a backup system for the crane,
- the type of the waterfront-pier (gravity or sheet-pile wall),
- the crane productivity (lifts per hour or tones per hour),
- the vulnerability or not of each component,
- the Intensity Measure (IM) type to be considered for the vulnerable classes,
- the seismic hazard input, in common for all systems in SYNER-G, either single scenario (one fault) or a complete hazard (see SYNER-G report D2.1, Franchin et al. 2011).

The berth (ship) length is estimated based on the pier’s operational depth, inverting the following regression equation, which gives the depth of the waterfront as a function of the ship overall length (Pachakis and Kiremidjian 2005).

\[
Draft = \begin{cases} 
-0.100 + 0.056 \cdot LOA & \text{for } LOA \leq 200 \text{ m} \\
7.668 + 0.018 \cdot LOA & \text{for } LOA > 200 \text{ m}
\end{cases} \quad (8.1)
\]

where Draft represents the depth of the waterfront, and LOA is the berth (ship) length.

In practice, for each waterfront, the minimum required berth length is estimated from (8.1). Then, the waterfront is divided into the greatest possible number of berth(s) with length longer than the minimum length required and each crane is assigned to its closest berth.

For each crane there must be a demand node of the electric power system (EPN). This demand node is connected to an EPN substation through non-vulnerable lines. In case of failure of power supply, cranes can work with their back-up power supply, if available. The functionality of the demand node is generally based on EPN system analysis, and it can be based on either capacity or pure connectivity analysis (see SYNER-G reports D5.2, Pinto et al. 2011 and section 2).

For the PI estimation, the following rules are set:

- Waterfront-pier (berth) $\rightarrow$ functional if Damage (D) < Moderate (for each IMtype).
- Crane $\rightarrow$ functional if D < Moderate AND there is electric power supply (from the electric network or from the back-up supply).
- Berth $\rightarrow$ functional if the waterfront and at least 1 crane is functional, otherwise $P_{bi} = 0$. 

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If the Berth is functional, the PI is set to the sum of the capacities relative to the functioning cranes that contains. Note that, in case of more than one crane, they can work simultaneously to load/upload containers from the same ship – the time the ship stays at each berth is then reduced.

- CraneCapacity\(k\) = \(r\times24\) TEU/day (Twenty-foot Equivalent Units per day) where \(r\) is the crane productivity. An assumption is made of 24 hours shifts.

\[ PI_{bi} = \sum_k \text{CraneCapacity}_k \]

- Pier \(\rightarrow\) \(PI_{pm} = \sum_i PI_{pi} \)
- Terminal \(\rightarrow\) \(PI_{tr} = \sum_m PI_{pm} \)
- Harbor \(\rightarrow\) \(PI_{H} = \sum_r PI_{tr} \)

2. Gate

The port performance at the gate is measured in terms of:

\[ TCoM = \text{total number of containers’ movements per DAY, in Twenty-foot Equivalent Units (TEU) (in the whole harbor facility)} \]

In this case the total number of containers’ movements per DAY is equal to the sum of total number of containers handled per DAY (TCoH) in all the container terminals that are connected to the gate through the road system.

For the assessment of TCoM, in addition to the input parameters reported above, it is necessary to consider the road system (RDN) that connects each terminal to the harbor’s gate, with all its important components (i.e., bridges, overpass, tunnels), and of course the buildings and the storage units inside the harbor that may collapse and block the road system (see SYNER-G reports D5.5, Pinto et al. 2012 and D5.1, Gehl et al. 2011). To this regard the necessary input is:

- link to a RND node for exit from each terminal
- link to a RND node for the harbor’s gate

The connectivity between terminals and harbor’s gate is based on the RDN system analysis (SYNER-G report D5.5, Pinto et al. 2012).

8.2.3 Bulk cargo terminals

1. Terminal

The terminal performance is measured in terms of:

\[ TC\text{aH} = \text{total cargo handled (loaded and unloaded) per DAY, in tones} \]

For the harbor, the sum of all container terminals is considered.

For the cargo, it is used the same methodology presented above for the container terminals, with the following modifications:

- The crane productivity \(r\) is given in tones per hour.
- CraneCapacity = \(r\times24\) tones/day (an assumption is made of 24 hours shifts).

2. Gate

The port performance at the gate is measured in terms of:
**TCaM** = total cargo movements per DAY, in tones (in the whole harbor facility)

In this case the total cargo movements per DAY are equal to the sum of total cargo handled per DAY in all the bulk cargo terminals that are connected to the gate through the road system. The additional parameters, with respect to TCaH, and the procedure adopted to assess TCaM are analogous to the ones described above for TCoM.

### 8.2.4 Software implementation

#### 8.2.5 HBR class

The HBR (harbor) class is the composition of HRBStructures, HRBEdges (or HRBSides) and HRBNodes classes, that are both abstract. HRBStructures is the generalization of terminals, piers and berths. HRBNodes is the generalization of cranes, while HRBedges (HRBsides) is the generalization of waterfronts.

![Class diagram for the harbor classes](image)

**Fig. 8.2 Class diagram for the harbor classes**

Structures have a logical hierarchy. Each terminal includes one or more piers, which are made up of one or more berths. Cranes and waterfronts own to one specific pier and terminal, information that is input by the user. The position and the configuration of berths are automatically assigned by the software. Following the naming convention set up for other systems, the harbor’s elements are classified in the following classes (Fig. 8.2):

- **Harbor**: part of the “network” class
- **HRBnode**: which includes Cranes
- **HRBside**: which includes Waterfronts
- **HRBstructure**: which includes Terminals, Piers, and Berths (internal class – not explicit to the user)
In the following, the properties of the HBR class are listed. The names follow the naming convention adopted for variables in developing the prototype software, whereby multi-word names have no blank spaces in between words and the latter are separated by capitalizing the initial letter of each word. It is split into five parts:

1. Several pointers, including:
   - **Parent**: this is a pointer to the parent object which, in this case, is the Infrastructure (the object from the Infrastructure class).
   - **Crane**: pointers to all the cranes in the system, objects from the Crane class.
   - **Waterfront**: pointers to all the cranes in the system, objects from the Waterfront class.
   - **Berth**: pointers to all the cranes in the system, objects from the Berth class.
   - **Pier**: pointers to all the cranes in the system, objects from the Pier class.
   - **Terminal**: pointers to all the cranes in the system, objects from the Terminal class.

2. Harbor system global properties, including:
   - Counters as nWaterfronts, nCranes, nBerths, nPiers, nTerminals, etc.
   - RDNnodeID: link to a RDN node, indicating the position in the road network of the Harbor’s gate.

3. Subclass characteristics that include the main features of sides, nodes and structures. As regards sides and nodes, such characteristics are common with the other systems and include structural characteristics (e.g., vulnerable or not, IM type), geographic positioning (e.g., coordinates) and site characteristics (e.g., Vs30, liquefaction susceptibility, landslide susceptibility). Structure characteristics include names, typologies, and other descriptive properties.

4. Properties that record the state of the HBR for each event, including the property states that consists of a nE×1 collection of properties that describe the current state for each of the nE events. States include the evaluation of PIs (TCoH, TCoM, TCaH, TCaM) and relative statistics.

5. Properties that assess the global performance of the HBR at the end of the simulation, including the property MAF, which is the Mean Annual Frequency of exceedance values for the considered system level PIs.

The definition of HBR class includes functions to assess PIs (and relative statistics), to retrieve the EPN and RDN states, to locate and characterize Berths, and to plot the system configuration and state. The average port performance and the Mean Annual Frequency (MAF) of exceedance of the PIs, are the main outputs of the simulation analysis. Apart from these, the analysis provides also the distribution of estimated damages and losses for specific events (either pre-selected, or selected from pre-defined annual frequency of exceedance of the PIs), the average damages/losses (averaged over the simulated events) and the correlation between each element functionality and the port PI (in order to identify the elements that tend to control the most the port performance).
8.2.6 HBR subclasses: node, side and structure

The HRBnode and HRBside classes include positioning and descriptive properties, general characteristics (e.g., crane capacity, waterfront depth, etc), reference structures’ IDs (pier and terminal), and methods assessing, for each event (scenario), physical damages and functional consequences. The performance of these classes is stored in a states collection (as above), which includes physical and functional state for each event (scenario).

The HRBstructure class includes positioning and descriptive properties, and links to HRBlinks and HRBnodes that each structure includes. The Berth subclass includes reference IDs to terminal and pier in which it is located. The Pier subclass includes a reference ID to the terminal to which it owns. The Terminal subclass includes a link to a RDN node, which indicates the starting position of the road leading to the harbor gate. The performance of these classes is stored in a states collection (as above), which includes PIs estimation and statistics at each subclass for each event (scenario).

8.3 THE CASE STUDY

8.3.1 General description

The port of Thessaloniki is the nodal point for the transport of goods coming from a large geographic inland, as it is located in a very strategic (geographically, politically and economically) area. It is the first export and transport harbor of Greece and is European Union’s closest port to the countries of Southeast Europe, as well as to the countries of the Black Sea and East Mediterranean. It covers an area of 1,550,000 m$^2$ and trades approximately 16,000,000 tons of cargo annually, having a capacity of 370,000 containers and 6 piers with 6,500m length (Fig. 8.3). In collaboration with the port authority (Thessaloniki Port Authority, THPA), various data was collected and implemented in GIS format for the construction, typological and functional characteristics of port facilities, including cargo and handling equipment, waterfront structures, electric power (transmission and distribution lines, substations), potable and waste water (pipelines), telecommunication (lines and stations), railway (tracks) and roadway (roads and bridge) systems as well as buildings and critical facilities.

![Fig. 8.3 Thessaloniki port](image)
The various components and systems existing inside the port facilities are illustrated in Fig. 8.4 and Fig. 8.5.

Fig. 8.4 Building facilities, waterfront structures, cargo handling equipment, telecommunication system and railway network of Thessaloniki’s port

Fig. 8.5 Water supply, waste-water, fire-fighting, electric power and fuel supply systems of Thessaloniki’s port
8.3.2 Seismic hazard

The description of the seismic hazard is provided in section 2.6.1 for the Thessaloniki case study. The same five seismic zones, provided by SHARE European research project (Arvidsson et al. 2010), geotechnical data and seismic ground motion are used. 10,000 simulations are carried out sampling earthquake events for these zones based on a Monte Carlo approach.

In Thessaloniki’s port, soil formations are characterized by very high liquefaction susceptibility, mainly due to loose, saturated, silty-sandy soils that prevail at the area. In previous studies (SRMLIFE 2003-2007), the evaluation of horizontal and vertical permanent ground displacements due to liquefaction (lateral spreading and settlements), has been performed for three scenarios with mean return periods \( T_m = 100, 475 \) and \( 1,000 \) years, using empirical and analytical procedures (Seed et al. 2003; Youd et al. 2001; EC8; Ishihara and Yoshimine 1992; Elgamal et al. 2001). In the port area, displacement values range between 0 and 30cm for settlements and 0 and 6cm for lateral spreading for the 475 year scenario.

8.3.3 System topology and characteristics

Following the methodological framework for the systemic analysis developed in SYNER-G, waterfront structures, cargo handling equipment, power supply system, roadway system and buildings are examined.

Waterfront structures, of a total 6.5km length, include concrete gravity quay walls with simple footing foundation and non-anchored components. The majority is block type gravity walls, while the new, actually under construction, part of Thessaloniki’s port includes caisson type structures. Backfill soils and rubble foundation include material aggregates with appropriate grain size distributions. Waterfront structures are defined with 17 sides and 24 nodes (pier-nodes).

Cargo handling equipment has non-anchored components without back-up power supply. 48 crane-nodes are considered in the analysis.

For the systemic analysis, two Terminals are considered; one container Terminal (6th pier) and one cargo Terminal (piers 2, 3, 4 and 5).

The electric power supply to the cranes is assumed to be provided from a demand node (substation) through non-vulnerable lines. These demand nodes are the distribution substations present inside the port facilities. They can be classified as low-voltage substations, with non-anchored components. Their functionality is determined on connectivity analysis of Thessaloniki’s EPN system (see section 2). In total 1 generator, 8 transmission substations, 17 distributions substations and 74 non-vulnerable lines are simulated. The geographical representation of Thessaloniki’s port waterfronts, cranes and electric power supply system is illustrated in Fig. 8.6.

A majority of the building and storage facilities are also considered in the analyses. The 88 building structures are allocated in 4 building blocks (BC).

The internal roadway network is rather simple with internal roads connecting the port gates to the terminals gates (Fig. 8.7).
8.3.4 Description of the input

The MATLAB environment provides through the function `xlsread` the capability of importing data organized within an Excel workbook. The latter was chosen as the format of the input file for the prototype software. Input for all components and systems within the port is prepared as a workbook within which, in general, each sheet correspond to a different system in the SYNER-G taxonomy. The input for `hrb`, `epn`, `rdn` and `bdg` sheets is outlined in the following.

8.3.5 Harbor components

Harbor components are comprised of 72 nodes and 17 sides. The nodes are subdivided in pier-edges (non-vulnerable) and (non-anchored) cranes (vulnerable). Edges include only
(gravity type) waterfronts. The fragility models used for cranes and waterfronts are expressed in terms of permanent ground displacement (PGD) and peak ground acceleration (PGA) (Table 8.1).

The first two cells in the first row of hrb sheet specify the number of edges (sides) and the number of nodes, 17 and 72, respectively. The following fields contain values used to determine the number of terminals, the consideration or not of EPN and RDN in the analysis, the IDs, the type and the RDN gate and exit nodes of each terminal. Also the fragility curves and functionality definition of the components are determined. The next rows, after the nodes keyword, specify in a standardized way (similar for all network/linelike systems) the nodes of the system.

In particular the information to be provided for each node is in the following order: localization, site properties, functional and related to seismic damageability, crane info and links. Localization is given in terms of latitude and longitude in degrees and altitude above sea level in metres. The site properties are specified in terms of Vs30, site class according to EC8, depth to groundwater, liquefaction and landslides susceptibility class, yield acceleration. The fields that are left empty are read from corresponding GIS shapefiles. Functional information for the harbor nodes is the type of node (either pier-edge or crane-non-anchored).

The next columns specify whether the node is vulnerable, and in that case, the IM(s) of the corresponding fragility model. Specific crane information include crane capacity (if ‘container’, capacity of cranes must be lifts/hour, if ‘bulk cargo’, capacity of cranes must be tones/hour), the existence or not of back-up power, the terminal and pier IDs. The interdependency of cranes with the electric power system is provided through links to EPN nodes.

The next part of the sheet, after the sides keyword, specifies in a standardized way (similar for all network/line-like systems) the edges of the system. In particular, the first two columns specify the edge connectivity (start and end nodes). The site properties are specified in terms of Vs30, site class, depth to groundwater in feet, liquefaction and landslides susceptibility class, yield acceleration.

The fields that are left empty are read from corresponding GIS shapefiles. Functional information includes the edge typology (gravity-waterfronts). As for the nodes, two columns specify whether the edge is vulnerable, and in case it is, which is the IM(s) for the corresponding fragility model. Specific waterfront information includes the operational depth, terminal and pier IDs. Pier operational length is compute from the coordinates.

### 8.3.6 Electric power network

In total 1 generator, 8 transmission substations, 17 distributions substations and 74 non-vulnerable (assumption) lines are simulated. For the sub-station, their type and IM is also provided. 48 demand nodes are defined for the electric power supply to cranes.

### 8.3.7 Roadway network and buildings

Both vulnerability analysis for the road network and the possible road blockage estimation from collapsed buildings are performed. For non-vulnerable road nodes their type can be either Traffic Analysis Zones “TAZ” (TAZ type is also provided) or intersection. Road
segments are all classified as principal two-way roads; their capacity is set to 500 vph, the free-flow speed to 50km/h. The Intensity Measure is PGD, while site class, liquefaction susceptibility class, landslide susceptibility class and yield acceleration are read from the respective maps. Road width, building-road distance, hierarchy and adjacent buildings are also necessary input for the road blockage analysis.

For each Building Block (BC) the total number of buildings inside the block and the percentage of each building typology are provided.

8.3.8 Fragility assessment

The fragility curves used for the vulnerability assessment of the components are shown in Table 8.1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Intensity measure</th>
<th>Fragility function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterfronts</td>
<td>PGD</td>
<td>HAZUS (NIBS 2004)</td>
</tr>
<tr>
<td></td>
<td>PGA</td>
<td>Kakderi and Pilitakis (2010)</td>
</tr>
<tr>
<td>Cranes/ cargo handling equipment</td>
<td>PGA, PGD</td>
<td>HAZUS (NIBS 2004)</td>
</tr>
<tr>
<td>Electric power substations</td>
<td>PGA</td>
<td>HAZUS (NIBS 2004)</td>
</tr>
<tr>
<td>(distribution)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric power substations</td>
<td>PGA</td>
<td>SRM-LIFE (2003-2007)</td>
</tr>
<tr>
<td>(transmission)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roads</td>
<td>PGD</td>
<td>HAZUS (NIBS 2004)</td>
</tr>
<tr>
<td>R/C and URM Buildings</td>
<td>PGA</td>
<td>Kappos et al. (2006)</td>
</tr>
<tr>
<td>Steel Buildings</td>
<td>PGA</td>
<td>HAZUS (NIBS 2004)</td>
</tr>
</tbody>
</table>

8.4 RESULTS

8.4.1 Main application results

The analysis results obtained from a plain MCS of 10,000 runs is presented in the following figures. The chosen number of runs have been shown to yield stable estimates for the considered PIs.

All PIs are normalized to the respective value referring to normal (non-seismic) conditions. For the container terminal this value is equal to $P_{Ia_{\text{max}}}=1,032$ TEUs per day. For the cargo terminal the max value for non-seismic conditions is equal to $P_{I_{o_{\text{max}}}}=43,512$ tones per day. These values refer to the max capacity of the port, since they are estimated assuming that all cranes are working at their full capacity for 24 hours a day.

Fig. 8.8 shows the moving average (mean) curves for TCoH (left) and TCaH (right), as well as the mean+stdv and mean-stdv curves for the two PIs. The figures indicate that the expected value of loss given the occurrence of an earthquake is higher for TCoH than for
TCaH. At the end of the analysis (10,000 runs) the moving average is stabilized. Comparison of the moving average (mean) curves for TCoM and TCaM with TCoH and TCaH respectively, shows no difference, meaning that no road closures are observed. This can be attributed to the small length of roadways considered in the analysis, as well as the limited number of low-height buildings in large building-road distances. Given the fact that no road closures are observed in the present analysis, results are presented hereinafter only for the TCoH and TCaH PIs.

Mean Annual Frequency (MAF) of exceedance values for all PIs are given in terms of normalized performance loss (1-\(\frac{\Pi}{\Pi_{\text{max}}^{\text{PI}}}\)). Fig. 8.9 shows the MAF of exceedance curves for TCoH and TCaH. For performance loss values below 20% TCaH yields higher values of exceedance frequency, while for performance loss over 20% TCoH yields higher values of exceedance frequency. The estimated MAF of exceedance curves (in terms of normalized performance loss) for TCoH and TCaH with and without interaction with building collapses (road blockage due to collapsed building is not considered in the analysis) are illustrated in Fig. 8.10. As expected, in both cases, there is no difference, since no road closures are observed; this type of interactions is not important in this particular case to the port’s overall performance. In other cases, for example in the Port Island in Kobe, it could be crucial. Fig. 8.11 compares the estimated MAF of exceedance curves for TCoH and TCaH when all interactions are taken into consideration (EPN and road closures) and no interactions are considered in the analysis. The effect of interaction (mainly of the EPN to cranes) can be very important for performance loss levels over 10% for TCoH and 5% for TCaH. As an example the TCoH performance loss is increased from 21% to 46% for \(\lambda=0.01\) (Tm= 100 years) when all interactions are included in the analysis. In the TCaH MAF curves, for performance loss levels of 50-60% there seems to be practically no change in the exceedance frequency values, and values with no interactions are higher than those corresponding to the all interactions case. This can be considered as the point of max performance loss for TCaH, only due to direct seismic damage occurred to cranes.

![Fig. 8.8 Moving average μ, μ+σ, μ-σ curves for TCoH (left) and TCaH (right).](image-url)
Fig. 8.9 MAF curve for TCoH and TCaH performance loss.

Fig. 8.10 MAF curves for TCoH (left) and TCaH (right) for Thessaloniki’s port, with and without interaction with building collapses.
Fig. 8.11 MAF curves for TCoH (left) and TCaH (right) for Thessaloniki’s port, with and without interaction with EPN and building collapses.

Fig. 8.12 and Fig. 8.13 show the level of correlation between the TCaH and the distribution of damages in cranes and non-functionality of electric power distribution substations respectively. In this way the most critical components can be defined in relation with their contribution to the performance loss of the system. All cranes have medium (40-70%) to high (over 70%) levels of correlation, indicating their great importance to the functionality of the overall port system. A higher level of correlation is estimated for the EPN distribution substations, with 40% of the components having values greater than 70%.

Fig. 8.12 Correlation of damaged cranes to port performance (PI=TCaH).
Fig. 8.13 Correlation of non-functional electric power distribution substations to port performance (PI=TCaH).

Fig. 8.14 and Fig. 8.15 show the expected functionality of port components for the event with the highest magnitude that corresponds to TCoH (TCoH loss=100%) and TCaH (TCaH loss=97%) performance loss with mean return period Tm=500 years (0.002 probability of exceedance) respectively. For both events, waterfronts structures (with the exception of one component) are functional, but the majority of cranes (85% and 88% respectively) are non-functional.

Fig. 8.14 Port components functionality for an event (#956, TCoH loss = 100%, TCaH loss = 53%, M=7.5, R= 135 km) that corresponds to TCoH with Tm=500 years.
8.4.2 Uncertainty issues

Several sources of uncertainties are inherent in the analysis. They are related among others to the seismic hazard and spatial correlation models, the fragility assessment or the functionality thresholds of each component. The epistemic uncertainty related to different fragility functions and functionality definitions was investigated performing sensitivity analysis with the use of alternative fragility curves and functionality thresholds for the waterfront structures. The vulnerability assessment of cranes could not be performed with alternative functions since HAZUS (NIBS 2004) curves are for the moment the only available in the literature. Also the functionality definition for cranes seems to be the most realistic one, since high levels of occurred damages usually necessitate the withdrawal or even replacement of the component.

In the main analysis, the HAZUS (NIBS 2004) curves are used for waterfronts for the case of ground failure (due to liquefaction), while for ground shaking with no liquefaction phenomena the fragility functions proposed by Kakderi and Pitilakis (2010) are adopted. This is the “Fragility 1” case of the initial analysis. In the alternative analysis, the fragility functions proposed by Ichii (2003), which take into account the occurrence of liquefaction, are used for the vulnerability assessment of waterfronts; this is the “Fragility 2” case.

In Fig. 8.16, the estimated MAF of exceedance curves (in terms of normalized performance loss) for TCoH and TCaH for both cases of fragility functions of waterfronts are compared; almost no differences are observed. This can be attributed to the small frequency of damage occurrence to the waterfront structures and the fact that the total port performance is mostly prescribed by the cranes functionality.

The functionality of waterfronts depends only on the level of seismic damage. In the main analysis, the waterfronts were considered fully functional if they sustained minor damages and non-functional for higher levels of damage; this is the “Functionality 1” case. An alternative analysis is performed (“Functionality 2”), where waterfront structures are considered as fully (100%) functional if they sustain minor damages and partially (50%) functional if they sustain moderate damages.
Fig. 8.17 compares the estimated MAF of exceedance curves (in terms of normalized performance loss) for TCoH and TCaH for the different functionality definitions of waterfront structures. In this case there is some difference in the MAF curves for TCaH with lower values of exceedance frequency for performance loss levels over 65%. In other words, high levels of performance loss correspond to lower probabilities of exceedance (or higher mean return periods). This is related to the fact that partial functionality of waterfronts is assumed for higher levels of damage, resulting in reduction of the port performance loss.

Fig. 8.16 MAF curves for TCoH (left) and TCaH (right) for Thessaloniki’s port using different fragility functions for waterfront structures.

Fig. 8.17 MAF curves for TCoH (left) and TCaH (right) for Thessaloniki’s port using different functionality definitions for waterfront structures.
8.5 CONCLUSIONS

The SYNER-G methodology and tools for the assessment of the systemic vulnerability and performance of harbors have been applied in the case of Thessaloniki’s port, the first export and transport harbor of Greece and the European Union’s closest port to the countries of Southeast Europe.

The seismic hazard is modeled in the SYNER-G prototype software through the object-oriented paradigm. Five seismic zones have been selected, based on SHARE European research project. A plain Monte Carlo simulation (MCS) has been carried out sampling earthquake events for these zones and computing selected performance indicators (PIs).

Port operations are simulated and system performance is assessed considering specific interdependencies between the components. Port Performance Indicators (PIs) are calculated based on the estimated damages and functionality loss of the different components.

The overall performance is expressed through the moving average $\mu$ and moving standard deviation $\sigma$ (averaged over simulations), as well as the Mean Annual Frequency (MAF) of exceedance of the PIs. The average loss is defined based on the moving average graph. Through the MAF graphs the annual probability of exceeding specific levels of loss can be defined and the loss for specific mean return period of the particular PI can be estimated. The earthquake event(s) that correspond to a particular return period (i.e., 500 year) are identified and maps with the distribution of damages are produced for this event(s). The correlation of each component to the system PIs is also estimated. This type of analysis is based on the results of each single event, and thus it preserves the information about systems’ topology and its behaviour in case of spatial correlated damages (related to single earthquakes). Thus, it allows identifying the most critical elements for the functionality of the system.

The interactions considered in the analysis are essential for the overall risk assessment. For example, it is shown that the performance loss of Thessaloniki’s port can be significantly increased due to possible failures of EPN substations that supply power to the cranes.

Several sources of uncertainties are inherent in the analysis. They are related among others to the seismic hazard and spatial correlation models, the fragility assessment or the functionality thresholds of each component. A probabilistic (Monte Carlo) approach is performed which samples earthquake events based on the methods and tools developed in SYNER-G. In this way, all the characteristics of each event (e.g., spatial correlations) are accounted for and preserved for the systemic analysis. The epistemic uncertainty related to different fragility functions and functionality definitions was investigated performing sensitivity analysis with the use of alternative fragility curves and functionality thresholds for the waterfront structures.
9 Conclusions/Final Remarks

The SYNER-G methodology and software tools have been applied and tested in selected case studies at urban and regional level. In particular, the following case studies have been undertaken and presented in this synthetic reference report:

At city/urban level:

1) The city of Thessaloniki, a high seismicity area in North Greece. The application includes buildings, road network, water supply system and electric power network with specific interdependencies between them. New analytical fragility curves developed for buildings (RC/masonry) and bridges based on the inventory of Thessaloniki area are also presented. An accessibility and shelter needs analysis is also performed.

2) A district of the city of Vienna in Austria, a low seismicity area. The application is performed in one district of the city. It includes buildings, road network, water supply system and electric power network with specific interdependencies between them.

At regional level:

4) The medium-pressure gas system of L’Aquila in Italy. The process makes use of probabilistic seismic hazard analysis, empirical relations to estimate pipeline response, fragility curves for the evaluation of facilities’ vulnerability and connectivity performance indicators to characterize the functionality of the network.

5) The road network of Calabria region in Southern Italy. A level I analysis has been performed, focusing the attention on the network’s pure connectivity, considering bridges and road pavements as vulnerable elements.

6) The electric power network of Sicily. A capacitive study has been performed, with power flow analysis that follows the analysis of short-circuit propagation, in which circuit breakers are active components playing a key role in arresting the short-circuit spreading. The substations are not modeled as vulnerable points; in fact, their full internal logic is modeled to account for partial functioning.

At complex infrastructure level:

7) A hospital system in Italy, composed of hospitals, area districts and a road network. The road network is deputed to connect districts and hospitals allowing the transportation of injured and sick people. To properly assess the response of the system, the vulnerability of the system components, i.e., hospitals and roads, as well as the interaction among them are accounted for. This represents a novelty of the proposed methodology with respect to common applications.

8) The harbor of Thessaloniki in Greece where system performance is assessed considering specific interdependencies between the components. Port Performance Indicators (PIs) are calculated based on the estimated damages and functionality loss of the different components.

Seismic hazard

A probabilistic approach is followed which samples earthquake events based on the hazard characterization of each area. Each sampled event represents a single earthquake
The results are then aggregated all over the sampled events. For each site of the grid the averages of primary IM from the specified GMPE were calculated, and the residual was sampled from a random field of spatially correlated Gaussian variables according to the spatial correlation model.

The source models provided in SHARE project are applied either as seismic zones (e.g. Thessaloniki case study, harbor of Thessaloniki) or as faults (e.g. transportation network in S. Italy and electric power network in Sicily). In other cases, specific faults are used as sources (e.g., Paganica fault in L’Aquila case study) or historical earthquakes are modeled (e.g., Vienna case study).

The performance of spatially distributed systems may be conditional upon the failure of many components each one being sensitive to different IMs. Therefore seismic input assessment has to take into account the possibility of the existence of a cross-correlation between IMs. To address this issue, spatial correlation models and conditional hazard approach are considered. For each site of the grid the averages of primary IM from the specified GMPE were calculated, and the residual sampled from a random field of spatially correlated Gaussian variables according to the spatial correlation model. The value of the primary IM at each site of the network (i.e., the vulnerable elements' sites) was then obtained interpolating the grid values.

Different amplification methods are available in the SYNER-G code (i.e Eurocode 8, NEHRP, Choi&Stewart, context-specific). Such methods amplify the shaking intensity measure (IM) at vulnerable sites a posteriori, i.e., after the ground motion calculation stage. It can also be used the within-GMPE amplification method, using the Vs30 values for site classification. In case no soil classification data are available IM values are computed on stiff soil conditions (e.g. transportation network in S. Italy and electric power network in Sicily).

**Fragility curves**

Appropriate fragility curves are selected for the components of each case study considering the typology/taxonomy of the network or infrastructure (see Reference Report 4, Kaynia 2013). In case of Thessaloniki application, new analytical fragility curves have also been developed for bridges and buildings respecting the specific typologies and features of the Thessaloniki structures.

**Systemic analysis and performance indicators**

Connectivity analysis is performed in most case studies (e.g. networks in Thessaloniki and Vienna, road network in South Italy, gas system in L’Aquila, hospital facilities in Italy). This is for simply due to lack of all required information or due to large computational demand required for a complete flow analysis. However, in case of road network at least, this type of analysis is coherent with the time-frame of the study, that is limited to rescue operations in the aftermath of the seismic event. The interest is the identification of the portions of the network which are critical with respect to the continued connectivity of the network. In case of electric power network in Sicily, a power flow analysis is performed. For complex systems (Thessaloniki harbor, health-care facilities) their internal logic and functions are simulated.

The risk assessment is performed in terms of appropriate performance indicators for each system. In this way, performance indicators that are able to quantify the degree to which the system is able to meet established specifications and/or customer requirements following an earthquake event give the quantitative measure of the functionality of each network.
Results

The overall performance of each network and system is expressed through the moving average $\mu$ and moving standard deviation $\sigma$ (averaged over simulations), as well as the Mean Annual Frequency (MAF) of exceedance of the PIs. The average loss is defined based on the moving average graph. Through the MAF graphs the annual probability of exceeding specific levels of loss can be defined and the loss for specific mean return period of the particular PI can be estimated. The earthquake event(s) that correspond to a particular return period (i.e., 500 year) are identified and maps with the distribution of damages are produced for this event(s).

Correlation of damaged components to system performance

In order to evaluate the contribution of certain components on the overall performance of the network the correlation between damaged components and system’s functionality is estimated.

In the case of Thessaloniki the correlation of each component (EPN, WSS, RDN) to the system PIs is estimated. This type of analysis is based on the results of each single event, and thus it preserves the information about systems' topology and its behavior in case of spatial correlated damages (related to single earthquakes). Thus, it allows identifying the most critical elements for the functionality of each system (i.e., the damaged components that more closely control the performance of the network).

In case of L’Aquila gas system, the percentages of sites vulnerable to PGD as well as the number of broken pipes and damaged M/R stations are correlated with the performance indicators of the network in order to evaluate possible linear dependences. The results indicate that the number of damaged M/R stations is better correlated with the considered PIs. The distributions of number of broken pipes and percentage of pipes vulnerable to PGD, conditional to the performance of the network are somewhat flat.

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 assessment or the functionality thresholds of each component.

In case of the Thessaloniki harbor, the epistemic uncertainty related to different fragility functions and functionality definitions is investigated through a sensitivity analysis with the use of alternative fragility curves and functionality thresholds for the waterfront structures. Similar results are obtained when different fragility curves are applied. This can be attributed to the small frequency of damage occurrence to the waterfront structures and the fact that the total port performance is mostly prescribed by the cranes functionality.

The effect of grid size for the computation of the primary IM was investigated in case of L’Aquila gas network, where different analyses were set up for three grids (i.e., 1 km, 2 km and 5 km). These were chosen via specific values of correlation of intra-event residuals for the primary IM. The results show that the larger the grid size, the larger is the approximation. As expected, coarser discretization tends to (slightly) underestimate the risk.

Socioeconomic analysis

A socio-economic analysis has been performed in the case of Thessaloniki. In particular, a GIS-based accessibility modeling has been implemented for shelter and healthcare services. It is a representative example, without considering the whole city and related networks. It is
shown that the SYNER-G methodology and analysis is an important tool for seismic risk management purposes before, during and after disaster. GIS based accessibility modeling can directly provide a vital support to disaster managers in terms of accessibility, location/allocation of available resources and service/catchment related issues. A shelter needs analysis has been also applied. The shelter model simulates households’ decision-making and considers physical, socio-economic, climatic, spatial and temporal factors in addition to modeled building damage states and utility loss. From the analysis, different SCDs are identified, as “Hot Spots” for shelter needs. These results can help for the planning of shelter allocation.

**General remarks and needs for future developments**

SYNER-G has developed a highly innovative and powerful methodology and tool for modern and efficient seismic risk assessment and management. It is probably the first time that so many important components of this complex problem have been put together in a comprehensive and scientifically sound way. The whole methodology and tools have been extensively validated with different case studies of variable typology and complexity. The numerous Reference Reports that have been prepared provide a detailed description of all output. The dissemination process is in progress, besides the three general workshops that have been organized in Thessaloniki, Vienna and Milano. Numerous journal papers and the publication of two books with the main results of the project are also in progress.

However there are still a lot of things that should be done in the near future. In the following some general remarks are outlined for future developments:

- The communication of results to stakeholders should be improved, shifting from the impact of an earthquake event to the impact of mitigation measures. It is important that the scientific community does not promise “zero losses” through appropriate mitigation measures, which will be never achieved, but rather a reduction of risk through constructive suggestions and recommendations.

- The active participation of stakeholders in future applications is essential for the improvement of results and for more practical use of outputs. It is also important to make the results more accessible and easily understood to the wider community of potential end users. For example the use of average values over a large number of Monte Carlo runs does not always provide a physical quantity that can be communicated to stakeholders. The homogeneity and clarity of the various presentation of the results of the applications is necessary to this extend.

- The SYNER-G software and tools (pre and post processing) needs to be further developed and improved in order to be more “friendly” to end-users; it should be also important to improve its computation performance.

- The proposed methodology represents the state-of-the-art in systemic risk, however is far more detailed than the level of data usually available (elements at risk, fragility curves). Therefore, it is necessary to invest in data mining to refine the inventories of elements at risk we have today. It is also necessary to invest more to quantify better the effects of various uncertainties, including the available data, in the accuracy of the results.
Argyroudis et al. 2013. D6.1- Application and validation study to the city of Thessaloniki (Greece), Deliverable of SYNER-G EC project.
Argyroudis S., Pitilakis K. 2011. Seismic Risk Performance of urban transportation systems considering site effects and interaction with the built environment. Proceedings of the 8th International Conference on Urban Earthquake Engineering, March 7-8, 2011, Tokyo Institute of Technology, Tokyo, Japan


Cartographic Center of Calabria region, http://www.centrocartografico.it/


Esposito S., Giovinazzi S., Iervolino I. 2011. D2.4-Definition of system components and the formulation of system functions to evaluate the performance of gas and oil pipeline, Deliverable of SYNER-G EC project.


Esposito S., Iervolino I. 2011b. D5.3 - Systemic vulnerability and loss for gas and oil networks, Deliverable of SYNER-G EC project.


Esposito S., Iervolino I. 2012b. D6.5 - Application and validation study to a gas pipeline network, Deliverable of SYNER-G EC project.


Kakderi K. and Pitilakis K. 2010. Seismic analysis and fragility curves of gravity waterfront structures. In Fifth International Conference on Recent Advances in Geotechnical


Loth C. and Baker J. 2011. Spatial cross-correlation of spectral accelerations at multiple periods: model development and risk assessment considering secondary earthquake effects. Project report, USGS award G10AP00046..


MAEviz software tool, http://mae.cee.illinois.edu/software_and_tools/maeviz.html


O’Rourke M.J., Liu X. 1999. Response of buried pipelines subjected to earthquake effects. MCEER Monograph No. 3.


OpenSHA (Open Source Seismic Hazard Analysis), http://www.opensha.org/

Pinto P., Cavaliere F., Franchin P., Lupoi A. 2012. D5.5-Systemic vulnerability and loss for transportation systems, Deliverable of SYNER-G EC project.
Pinto P.E., Cavaliere F., Franchin P. and Vanzi I. 2011. D5.2 - Systemic vulnerability and loss for electric power systems, Deliverable of SYNER-G EC project.
Pinto, P.E., Cavaliere F., Franchin P. and Vanzi I. 2011b. D2.3 - Definition of system components and the formulation of system functions to evaluate the performance of electric power systems, Deliverable of SYNER-G EC project.
Raptakis D. 1995. Contribution to the determination of the geometry and the dynamic characteristics of soil formations and their seismic response, Ph.D. Thesis (in Greek), Dep. of Civil Engineering, Aristotle University of Thessaloniki


Abstract

The SYNER-G project aims at developing a methodology to evaluate the seismic vulnerability to earthquakes of a complex system of interconnected infrastructural systems of regional/urban extension. This report summarizes the application of the SYNER-G methodology and tools to selected case studies of regional and urban extension: the city of Thessaloniki; the city of Vienna; the gas system of L’Aquila in Italy; the road network of Calabria region in Southern Italy; the electric power network of Sicily; a hospital facility in Italy; the harbor of Thessaloniki. For each case study the following items are given: general description of the test site, seismic hazard issues, systemic vulnerability methodology, software developments and implementation, system topology and characteristics, description of the input, results of the application. Through these studies the different steps of the SYNER-G methodology are validated and demonstrated.
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