### PROJECT INFORMATION

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**REVISION: Final**

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Abstract

This synthetic report summarizes the application of SYNER-G methodology and tools to selected case studies of regional and urban extension: the city of Thessaloniki in Greece; the city of Vienna in Austria; the gas system of L'Aquila in Italy; the road network of Calabria region in Southern Italy; the electric power network of Sicily (Italy); a hospital facility and a regional health-care system in Italy; the harbor of Thessaloniki in Greece. For each case study the following items are briefly presented: general description of the test site, seismic hazard issues, systemic vulnerability methodology, software developments and implementation, system topology and characteristics, description of the input and finally the results of the application.

Keywords: SYNER-G methodology, validation studies, synthetic report
Acknowledgments

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1 Introduction

This report presents, in a synthetic way the application of the SYNER-G methodology and tools to the 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 and health-care regional system in Italy, harbor of Thessaloniki in Greece) 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.

This report is related to other SYNER-G reference reports and deliverables, which are needed for a comprehensive understanding of the applications (e.g. Pitilakis and Argyroudis 2013; Kaynia et al. 2011; Gehl et al. 2011; Franchin et al. 2011; Pinto et al. 2011a; Weatherhill et al. 2011; Franchin et al. 2011; Pinto et al. 2012 among others).
2 The case studies

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 (Fig. 2.1). 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 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). An accessibility analysis to hospital facilities and shelter areas considering the damages in RDN is also performed and a shelter demand analysis based on a multi-criteria approach is applied.

Fig. 2.1 Sub-city districts (SCD) of Thessaloniki study area as defined by Urban Audit
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 (Fig. 2.2). 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 OOFIMS runner performed the probabilistic analysis including buildings, water supply system, road and electric power network with specific interdependencies between them.

Fig. 2.2 The city of Vienna with the part of the 20th district
The gas system of L’Aquila in Italy. The medium-pressure portion of the L’Aquila gas system was selected (Fig. 2.3). 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 landslides.

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 (Fig. 2.4). 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 (Fig. 2.5); their full internal logic is modeled to account for partial functioning. The network is composed of 181 nodes and 220 transmission lines.

Hospital facility and health-care regional system in Italy. The response of a regional health-care system depends on the hospital’s performance but also on 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. A hypothetical region with an
infrastructure (system of systems) composed of a road network (RDN) and a health care system (HCS) was examined (Fig. 2.6).

Fig. 2.6 The hypothetical study area

The vulnerability assessment is based on a representative large medical centre located in south Italy which should be able to provide all the “essential” medical services required to take care of the victims of a natural disaster under emergency conditions. The facility consists of a main body composed of two separate RC buildings connected by two tower structures (Fig. 2.7). The vulnerability of the facility is evaluated by non-linear dynamic analyses taking into account the response of structural as well as non-structural elements.

Fig. 2.7 General plan of the examined hospital system
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 (Fig. 2.8). 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 accounted for in the analysis are the supply of EPN to cranes and the road closures due to building collapses.
### Table 2.1. Summary of elements at risk in each case study

<table>
<thead>
<tr>
<th>Network</th>
<th>Vulnerable Components</th>
<th>Nodes</th>
<th>Edges</th>
<th>Comments</th>
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<tr>
<td><strong>City of Thessaloniki</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BDG</td>
<td>buildings</td>
<td>27,738 buildings (92% R/C, 8% masonry)</td>
<td>-</td>
<td>20 SCDs, buildings, 2,630 building blocks, population: 376,589 (municipality), 790,824 (city) population</td>
</tr>
<tr>
<td>RDN</td>
<td>roads, bridges</td>
<td>594 (15 external nodes, 127 TAZ’s centroids, 452 simple intersections)</td>
<td>674 (60 bridges)</td>
<td></td>
</tr>
<tr>
<td>EPN</td>
<td>substations</td>
<td>30 (1 generator/ transformation substation, 8 transmission/transformation substations, 21 demand nodes)</td>
<td>29 lines</td>
<td></td>
</tr>
<tr>
<td>WSS</td>
<td>pipelines</td>
<td>477 (437 demand nodes, 21 pumping stations, 11 tanks)</td>
<td>601 (24 diameter values between 500-3,000mm, construction materials: asbestos cement, cast iron, PVC, welded steel)</td>
<td></td>
</tr>
<tr>
<td><strong>City of Vienna/ Deterministic analysis</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BDG</td>
<td>buildings</td>
<td>550 (30% R/C, 70% masonry)</td>
<td>-</td>
<td>Briqittenau district (20th district of Vienna)</td>
</tr>
<tr>
<td>RWN</td>
<td>tunnels, bridges</td>
<td>34 bridges, 21 tunnels</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>RDN</td>
<td>roads, bridges</td>
<td>67 bridges, 9617 road segments</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>City of Vienna/ Probabilistic analysis</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BDG</td>
<td>Buildings</td>
<td>550 (30 % R/C, 70 % masonry)</td>
<td>-</td>
<td>3 SCDs, 11 Building Census, population: 35402</td>
</tr>
<tr>
<td>RDN</td>
<td>roads</td>
<td>101 (9 TAZ’s centroids, 4 external nodes, 88 simple intersections)</td>
<td>161</td>
<td></td>
</tr>
<tr>
<td>WSS</td>
<td>pipelines</td>
<td>110 ( 107 demand nodes, 3 tanks)</td>
<td>108 (4 diameter values: 1600, 1200, 800 and 500mm,</td>
<td></td>
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### D6.8 - Pilot studies and application of SYNER-G methodology

<table>
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<tr>
<th>Component</th>
<th>Description</th>
<th>Details</th>
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<tbody>
<tr>
<td>EPN substations</td>
<td>construction material: cast iron</td>
<td>109 (2 generators, 5 transmission/transformation substations, 102 demand nodes)</td>
</tr>
<tr>
<td>GAS pipelines, M/R stations</td>
<td></td>
<td>602 (3 sources, 209 Reduction Groups, 390 joints)</td>
</tr>
<tr>
<td>RDN road segments</td>
<td></td>
<td>2861 (422 TAZ’s centroids and simple intersections)</td>
</tr>
<tr>
<td>EPN micro-components in substations</td>
<td></td>
<td>181 (1 balance node, 5 supply nodes, 175 demand nodes)</td>
</tr>
<tr>
<td>Hospital facility and health-care system in Italy</td>
<td></td>
<td>12 bridges, 8 TAZs</td>
</tr>
<tr>
<td>The harbor of Thessaloniki</td>
<td></td>
<td>72 (48 cranes, 24 pier edges)</td>
</tr>
<tr>
<td>HRB cranes</td>
<td></td>
<td>75 (1 generator, 8 transmission substations, 17 distributions substations, 49 demand nodes)</td>
</tr>
<tr>
<td>EPN substations</td>
<td></td>
<td>74 lines</td>
</tr>
<tr>
<td>BDG buildings</td>
<td></td>
<td>88 buildings (72% R/C, 9% URM, 19% Steel)</td>
</tr>
<tr>
<td>RDN road segments</td>
<td></td>
<td>5 (road segments)</td>
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</table>
3 Fragility curves

The fragility curves used in the applications are summarized in Table 3.1 for each vulnerable component. The fragilities curves are compiled and described in Reference Report 4 (Kaynia 2013).

Table 3.1 Fragility curves used in the case studies

<table>
<thead>
<tr>
<th>System</th>
<th>Component</th>
<th>Classification</th>
<th>IM Type</th>
<th>Fragility curves</th>
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<tbody>
<tr>
<td>Thessaloniki case study</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPN</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>WSS</td>
<td>pipelines</td>
<td>pipe material and diameter, joint type, soil type</td>
<td>PGV, PGD</td>
<td>ALA (2001)</td>
</tr>
<tr>
<td>BDG</td>
<td>RC buildings</td>
<td>see Table 3.2, Table 3.3</td>
<td>PGA</td>
<td>see SYNER-G report D6.1 (Argyroudis et al. 2013)</td>
</tr>
<tr>
<td></td>
<td>masonry buildings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RDN</td>
<td>bridges</td>
<td>see Table 3.4</td>
<td>PGA</td>
<td>see SYNER-G report D6.1 (Argyroudis et al. 2013)</td>
</tr>
<tr>
<td></td>
<td>road pavements</td>
<td>urban roads (2 lanes)</td>
<td>PGD</td>
<td>NIBS (2004)</td>
</tr>
<tr>
<td></td>
<td>roads (blockage due to buildings collapses)</td>
<td>road-building distance, building height</td>
<td>PGA</td>
<td>SYNER-G (Gehl et al. 2011)</td>
</tr>
<tr>
<td>Vienna case study</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BDG</td>
<td>RC buildings</td>
<td>see Table 3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>masonry buildings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RDN</td>
<td>road pavements</td>
<td>urban roads (2 lanes), major roads (4 lanes)</td>
<td>PGD</td>
<td>NIBS (2004)</td>
</tr>
<tr>
<td>WSS</td>
<td>pipelines</td>
<td>pipe material and diameter, joint type, soil type</td>
<td>PGV, PGD</td>
<td>ALA (2001)</td>
</tr>
<tr>
<td>EPN</td>
<td>transmission stations</td>
<td>open, mixed and closed-type</td>
<td>PGA</td>
<td>SRM-LIFE (2003-2007)</td>
</tr>
<tr>
<td>L’ Aquila case study (gas network)</td>
<td>pipes</td>
<td>pipe material, pipe diameter</td>
<td>PGV, PGD</td>
<td>ALA (2001)</td>
</tr>
<tr>
<td>Transportation network in Italy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RDN</td>
<td>bridges</td>
<td>main road, secondary road</td>
<td>PGA</td>
<td>see SYNER-G report D3.6 (Fardis et al. 2011)</td>
</tr>
<tr>
<td></td>
<td>road pavements</td>
<td>main road, secondary road</td>
<td>PGD</td>
<td>see SYNER-G report D3.7 (Kaynia et al. 2011)</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 and health-care system 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) |

### RDN

| Bridges | single-bent overpasses, two-bent overpasses | PGA |

### Harbor of Thessaloniki

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranes/ cargo handling equipment</td>
<td>non-anchored</td>
<td>PGA, PGD</td>
<td>NiBS (2004)</td>
</tr>
</tbody>
</table>

### EPN

| Distribution substations | low voltage, non-anchored | PGA | NiBS (2004) |

### Transmission stations

| Transmission stations | open, mixed and closed-type with low level of building seismic design | PGA | SRM-LIFE (2003-2007) |

### RDN

| Road pavements | urban roads (2 lanes) | PGD | NiBS (2004) |

### BDG

<table>
<thead>
<tr>
<th>R/C and URM buildings</th>
<th>Masonry: urm, stone/brick, low/medium height R/C: structural system, infill walls, building height, level of seismic design</th>
<th>PGA</th>
<th>Kappos et al. (2006)</th>
</tr>
</thead>
<tbody>
<tr>
<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>

### Table 3.2 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>Infilled frames</td>
<td>1959</td>
<td>L</td>
<td>0.25</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.30</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.41</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>1984</td>
<td>L</td>
<td>0.23</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.32</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.39</td>
<td>0.92</td>
</tr>
<tr>
<td>Pilotis</td>
<td>1959</td>
<td>L</td>
<td>0.12</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.12</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.27</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>1984</td>
<td>L</td>
<td>0.11</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>0.14</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.31</td>
<td>0.66</td>
</tr>
<tr>
<td>Dual</td>
<td>1959</td>
<td>L</td>
<td>0.12</td>
<td>0.18</td>
</tr>
</tbody>
</table>

---

24
### Table 3.3 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><strong>Low-rise</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rigid floors</td>
<td>0.02</td>
<td>0.24</td>
</tr>
<tr>
<td>Flexible floors</td>
<td>0.02</td>
<td>0.12</td>
</tr>
<tr>
<td><strong>Mid-rise</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rigid floors</td>
<td>0.04</td>
<td>0.18</td>
</tr>
<tr>
<td>Flexible floors</td>
<td>0.02</td>
<td>0.06</td>
</tr>
</tbody>
</table>

### Table 3.4 Bridge types in the Thessaloniki study area

<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>Monolithic connection, continuous deck</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 and bearings, 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>B07</td>
<td>restrained</td>
<td>2003</td>
<td>single-column</td>
<td></td>
</tr>
<tr>
<td>B08</td>
<td>restrained</td>
<td>2003</td>
<td>single-column</td>
<td></td>
</tr>
<tr>
<td>B15</td>
<td>restrained</td>
<td>2002</td>
<td>single-column</td>
<td></td>
</tr>
<tr>
<td>B20</td>
<td>free</td>
<td>1985</td>
<td>wall</td>
<td></td>
</tr>
<tr>
<td>B21</td>
<td>free</td>
<td>1985</td>
<td>wall</td>
<td></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>
Table 3.5 Fragility curves used in Vienna test case for RC and masonry buildings

<table>
<thead>
<tr>
<th>Fragility curves</th>
<th>IMT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RC buildings</strong></td>
<td></td>
</tr>
<tr>
<td>Borzi et al. 2007-RC - 8 storeys-seismicallydesigned (c = 10 %)</td>
<td>PGA</td>
</tr>
<tr>
<td>Borzi et al. 2007-RC - 4 storeys-seismicallydesigned (c = 10 %)</td>
<td>PGA</td>
</tr>
<tr>
<td>Erberik 2008 - RC - low rise bare frame LRBR</td>
<td>PGV</td>
</tr>
<tr>
<td>Erberik 2008 - RC - mid-rise bare frame MRBR</td>
<td>PGV</td>
</tr>
<tr>
<td>Erberik 2008 - RC - mid-rise infilled frame MRIR</td>
<td>PGV</td>
</tr>
<tr>
<td>Erberik and Elnashai 2004 – RC flat slab - mid-rise infilled frame MRINF</td>
<td>Sd</td>
</tr>
<tr>
<td>Kappos et al. 2003 - RC3.1-HR-HC</td>
<td>PGA</td>
</tr>
<tr>
<td>RISK-UE 2003 - RC moment frame-HR-HC-UTCB hybrid approach</td>
<td>Sd</td>
</tr>
<tr>
<td>RISK-UE 2003 - RC moment frame - LR-HC-UTCB hybrid approach</td>
<td>Sd</td>
</tr>
<tr>
<td>RISK-UE 2003 - RC moment frame - MR-HC-IZIIS approach</td>
<td>Sd</td>
</tr>
<tr>
<td>Vargas et al. 2010 - RC - 8 storeys</td>
<td>Sd</td>
</tr>
<tr>
<td><strong>Masonry buildings</strong></td>
<td></td>
</tr>
<tr>
<td>Borzi et al. 2008b - MA Brick - High percentage voids - 2 storeys</td>
<td>PGA</td>
</tr>
<tr>
<td>LESSLOSS 2005-adobe and rubble stone - 8-15 storeys - Lisbon</td>
<td>Sd</td>
</tr>
<tr>
<td>RISK-UE 2003 - M12-HR-UNIGE approach</td>
<td>Sd</td>
</tr>
<tr>
<td>Borzi et al. 2008b - MA brick-low percentage voids - 4storeys</td>
<td>PGA</td>
</tr>
<tr>
<td>RISK-UE 2003 - M12-LR-UNIGE approach</td>
<td>Sd</td>
</tr>
</tbody>
</table>
4 Seismic and geotechnical hazard

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 is modeled using appropriate correlation models. For each site of the grid the averages of primary IM from the specified GMPE are calculated, and the residual is 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. Depending on the available information for site characterization an amplification method is selected.

For the liquefaction and landslide 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).

The main features for the seismic and geotechnical hazard assessment are outlined in Table 4.1 for each case study. For more information the reader is referred to SYNER-G reference report 6 (Pitilakis and Argyroudis 2013).
Table 4.1 Summary of seismic and geotechnical hazard for the case studies

<table>
<thead>
<tr>
<th>Case study</th>
<th>Seismic Hazard</th>
<th>GMPE</th>
<th>Soil amplification</th>
<th>Liquefaction susceptibility</th>
<th>Landslide susceptibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>City of Thessaloniki</td>
<td>areaFault: 5 zones/ SHARE project</td>
<td>Akkar and Bommer (2010)</td>
<td>EC8 (A, B, C soil classes)</td>
<td>Very high, moderate, none / HAZUS (NIBS 2004)</td>
<td>no</td>
</tr>
<tr>
<td>City of Vienna/ Deterministic analysis</td>
<td>- Neulengbach earthquake (1590), M=6.0</td>
<td>Campbell and Borzognia (2006)</td>
<td>EC8 (A, B, C soil classes)</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>City of Vienna/ Probabilistic analysis</td>
<td>areaFault: 4 seismic zones /SHARE project</td>
<td>Akkar and Bommer (2010)</td>
<td>EC8 (A,B,C soil classes)</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>The gas system of L’Aquila in Italy</td>
<td>simpleFaultGeometry: Paganica fault Mw=6.3, occurrence rate = 1/750</td>
<td>Akkar and Bommer (2010)</td>
<td>Vs30 values/ Akkar and Bommer (2010)</td>
<td>no</td>
<td>classification according to lithological group, slope angle, and ground-water condition, Kc=0.05-0.6g/ HAZUS (NIBS 2004)</td>
</tr>
<tr>
<td>The electric power network of Sicily</td>
<td>simpleFaultGeometry: 18 faults/ Italian DISS and SHARE project</td>
<td>Akkar and Bommer (2010)</td>
<td>no soil classification data available, IM values computed on rock</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Hospital facility and health-care system in Italy</td>
<td>areaFault: 3 seismic zones (hypothetical)</td>
<td>Akkar and Bommer (2010)</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>The harbor of Thessaloniki</td>
<td>areaFault: 5 zones/ SHARE project</td>
<td>Akkar and Bommer (2010)</td>
<td>EC8 (A, B, C soil classes)</td>
<td>very high/ HAZUS (NIBS 2004)</td>
<td>no</td>
</tr>
</tbody>
</table>
5 Systemic vulnerability analysis and software implementation

The main features for the systemic vulnerability analysis and the software implementation are given below for each case study. For more information the reader is referred to SYNER-G reference report 6 (Pitilakis and Argyroudis 2013).

5.1 CITY OF THESSALONIKI, GREECE

Buildings

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

- 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. 5.1 and described in detail by Gehl et al. (2011).

![Fig. 5.1 Flowchart of the building class computation](image)

Electric power network

The analysis performed in this application is based on connectivity only. Power flow analysis (see D5.2 Pinto et al. 2011a) 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 (assumed non-vulnerable in this application), and (3) distribution substations and demand nodes, are analysed separately, in order to retrieve their functionality (isolated/non-isolated state) of each demand node. Each node is removed from the system when non-functional. In particular, the functionality of transmission substations is based on their physical damages (non-functional with damages ≥ moderate) and to their connectivity to the generator. When vulnerable, the functionality of distribution substations is based on their physical damages (non-functional with damages ≥ moderate) and to their connectivity to functional distribution substations. 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/transformation station (over-high voltage, 400-150 kV) is considered as generator connected to the transmission/transformation stations (high voltage, 150kV-20kV). Demand nodes (non-vulnerable) are located at the pumping stations of the WSS. The interaction with the WSS is simulated through the connection of WSS pumping stations with the reference EPN load bus (here substation), as an approximation of analysing the whole EPN distribution system.

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 (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).

**Water supply system**

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).

**Road network**

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 (see also section 5.4)

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.

During the simulation, an edge can be in the following states:

- Broken: 0 or 1 (direct physical failure)
- BlockedbyBridge: 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. 5.2 is adopted to update the adjacency matrix (i.e., use of an OR gate).

**Fig. 5.2 Update procedure of the adjacency matrix**

### 5.2 CITY OF VIENNA, AUSTRIA

The same methods as described in the Thessaloniki case study are applied (section 5.1).
5.3 GAS SYSTEM (APPLICATION IN L’AQUILA, ITALY)

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.

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. 5.3, 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.

![Fig. 5.3 Class diagram for the gas distribution network](image)

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. Methods refer to functions used to evaluate the state of the network or of each component of the system.

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).

5.4 ROAD NETWORK (APPLICATION IN CALABRIA REGION, SOUTHERN ITALY)

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.

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.

Fig. 5.4 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.

![Fig. 5.4 Class diagram for the RDN class](image-url)
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 (Pinto et al. 2012). 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.

5.5 ELECTRIC POWER NETWORK (APPLICATION IN SICILY)

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.

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.

Fig. 5.5 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.
5.6 HOSPITAL FACILITY AND REGIONAL HEALTH-CARE SYSTEM (APPLICATION IN ITALY)

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 response of the system depends not only on the performance of each component but also on their mutual interactions.

The consequences on a hospital facility are expressed through the $HTC$ index, the number of surgeries that can be operated after the seismic event, which is probabilistically estimated by taking into account not only the physical damages to the building, but also the performance of non-structural elements, the preparedness of the staff and the effectiveness of the emergency procedure.

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 components of the system and the “hospitalisation” model developed for this study are described in some more detail in Pitilakis and Argyroudis (2013).

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.

5.7 HARBOR (APPLICATION IN THESSALONIKI)

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. 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. 5.6). 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).

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**Fig. 5.6 Functionality simulation of port facilities**
5.8 SUMMARY OF SYSTEMIC VULNERABILITY ANALYSIS

In the following table the main features of the systemic analysis for each case study are summarized.

**Table 5.1 Systemic analysis for the case studies**

<table>
<thead>
<tr>
<th>Components</th>
<th>Interactions with</th>
<th>Analysis</th>
<th>Performance indicators</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>City of Thessaloniki</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BDG (masonry, RC)</td>
<td>EPN, WSS</td>
<td>systemic</td>
<td>yielding &amp; collapsed buildings, deaths, injuries, displaced people</td>
<td>MCS (10,000 runs)</td>
</tr>
<tr>
<td>EPN (substations)</td>
<td>-</td>
<td>connectivity</td>
<td>Electric power network Connectivity Loss (ECL)</td>
<td></td>
</tr>
<tr>
<td>WSS (pipes, pumping stations)</td>
<td>EPN</td>
<td>connectivity</td>
<td>Water Connectivity Loss (WCL)</td>
<td></td>
</tr>
<tr>
<td>RDN (road segments, bridges, overpasses)</td>
<td>BDG</td>
<td>connectivity</td>
<td>Simple Connectivity Loss (SCL), Weighted Connectivity Loss (WCL)</td>
<td></td>
</tr>
<tr>
<td>City of Vienna</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BDG (masonry, RC)</td>
<td>EPN, WSS</td>
<td>systemic</td>
<td>yielding &amp; collapsed buildings, deaths, injuries, displaced people</td>
<td>MCS (10,000 runs)</td>
</tr>
<tr>
<td>RDN (roads)</td>
<td>BDG</td>
<td>connectivity</td>
<td>Simple Connectivity Loss (SCL), Weighted Connectivity Loss (WCL)</td>
<td></td>
</tr>
<tr>
<td>WSS (pipes)</td>
<td>EPN</td>
<td>connectivity</td>
<td>Water Connectivity Loss (WCL)</td>
<td></td>
</tr>
<tr>
<td>EPN (substations)</td>
<td>-</td>
<td>connectivity</td>
<td>Electric power network Connectivity Loss (ECL)</td>
<td></td>
</tr>
<tr>
<td>The gas system of L’Aquila in Italy</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>GAS (M/R stations, pipes)</td>
<td>-</td>
<td>connectivity</td>
<td>Connectivity Loss (CL), Serviceability Ratio (SR)</td>
<td>MCS</td>
</tr>
<tr>
<td>The road network in Calabria region, Southern Italy</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>RDN (roads, bridges)</td>
<td>-</td>
<td>connectivity</td>
<td>System-level: Simple Connectivity Loss (SCL), Weighted Connectivity Loss (WCL)</td>
<td>MCS (20,000 runs), ISS (2,000 runs), ISS-KM (200 runs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Component-level: Minimum travel time, Terminal Reliability</td>
<td></td>
</tr>
<tr>
<td>The electric power network of Sicily</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPN (substations)</td>
<td>-</td>
<td>capacitive study (power flow analysis)</td>
<td>System-level: Connectivity Loss (CL), Power Loss (PL), System Serviceability Index (SSI)</td>
<td>MCS (20,000 runs), Importance Sampling (ISS)</td>
</tr>
</tbody>
</table>
### Hospitals system at regional scale in Italy

<table>
<thead>
<tr>
<th>RDN (bridges)</th>
<th>Hospital facilities</th>
<th>System analysis including vulnerable hospitals and bridges</th>
<th>Casualties (divided in two categories) that are not allocated in hospitals. Maximum hospitalisation travel time. Hospitals seismic risk (probability of not being able to provide the required medical treatments to victims).</th>
<th>MCS (10,000 runs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDN</td>
<td>RDN</td>
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</tbody>
</table>

### The harbor of Thessaloniki

<table>
<thead>
<tr>
<th>Cranes</th>
<th>Waterfront structures</th>
<th>EPN</th>
<th>Port performance analysis</th>
<th>Container Terminals:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td><strong>TCoH</strong> = total number of containers handled (loaded and unloaded) per DAY, in Twenty-foot Equivalent Units (TEU)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>TCoM</strong> = total number of containers’ movements per DAY, in Twenty-foot Equivalent Units (TEU) (in the whole harbor facility)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Bulk cargo terminals</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>TCaH</strong> = total cargo handled (loaded and unloaded) per DAY, in tones</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>TCaM</strong> = total cargo movements per DAY, in tones (in the whole harbor facility)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>EPN</th>
<th>BDG</th>
<th>MCS (10,000 runs)</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

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Voltage Ratio (VR) (2,000 runs), Importance Sampling with k-means clustering (ISS-KM) (200 runs)
6 Results

In the followings, representative results are given for each case study.

6.1 CITY OF THESSALONIKI

6.1.1 Electric power network

Fig. 6.1 shows the moving average (mean) curve for ECL 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 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. 6.2 shows the MAF of exceedance for ECL. The ECL with mean return period \(T_m=500\) years (\(\lambda=0.002\)) 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. 6.4. 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. 6.1 Moving average \(\mu, \mu+\sigma, \mu-\sigma\) curves for ECL](image1)

![Fig. 6.2 MAF curve for electric power network connectivity loss (ECL)](image2)
Fig. 6.3 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.

![Fig. 6.3 Correlation of non-functional transmission substations to electric power network connectivity loss.](image)

![Fig. 6.4 Electric power network damages for an event (#6415 M=7.4, R=40km) that corresponds to ECL with Tm=500 years](image)
6.1.2 Water supply system

Fig. 6.5 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. 6.6 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. 6.7 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. 6.8 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 Tm=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.
6.1.3 Buildings

Fig. 6.9, 6.10, 6.11 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. 6.12, 6.13, 6.14 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. 6.16, 6.17, 6.18. 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. 6.15 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.
D6.8 - Pilot studies and application of SYNER-G methodology

Fig. 6.9 Moving average $\mu$, $\mu+\sigma$, $\mu-\sigma$ curves for deaths (average: 4)

Fig. 6.10 Moving average $\mu$, $\mu+\sigma$, $\mu-\sigma$ curves for injuries (average: 11)

Fig. 6.11 Moving average $\mu$, $\mu+\sigma$, $\mu-\sigma$ curves for displaced persons/good weather (average: 6280)
D6.8 - Pilot studies and application of SYNER-G methodology

Fig. 6.12 MAF curve for deaths

Fig. 6.13 MAF curve for injuries

Fig. 6.14 MAF curve for displaced persons
Fig. 6.15 Correlation of damaged EPN and WSS components to displaced people
Fig. 6.16 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 $T_m=500$ years.
Fig. 6.17 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. 6.18 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
6.1.4 Roadway network

Fig. 6.19 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. 6.19 Moving average $\mu$, $\mu+\sigma$, $\mu-\sigma$ curves for SCL (left) and WCL (right).

Fig. 6.20 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. 6.21 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. 6.22 and Fig. 6.23 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 Monastiriou avenue with railway (Mytilinakia), interchange of Monastiriou 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. 6.24 shows the expected distribution of damages for the event with the highest magnitude that corresponds to connectivity loss (WCL=18%) with mean return period Tm=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. 6.20 MAF curve for simple (SCL) and weighted (WCL) connectivity loss.

Fig. 6.21 MAF curve for weighted connectivity loss (WCL) for the road network of Thessaloniki, with and without interaction with building collapses.
Fig. 6.22 Correlation of broken edges (bridges) to road network connectivity (PI=WCL)

Fig. 6.23 Correlation of blocked by buildings edges to road network connectivity (PI=WCL)
6.1.5 Shelter demand analysis

The estimated damages and losses for buildings, utility and road networks are used as input to the integrated shelter need model developed in SYNER-G. In particular, a Shelter Needs Index (SNI) is estimated for each one of the 20 Sub City Districts (Fig. 6.25) based on: a) the displaced people estimates for bad and good weather conditions, which are a function of the building damages (BDG) and the utility losses (WSS and EPN), b) the desirability of people to evacuate and c) their access to resources. Criteria b) and c) are evaluated based on indicators from the Urban Audit survey (e.g. age, family status, unemployment rate, education level etc).
6.1.6 Accessibility analysis

The estimated damages and losses of the road network provided input for the accessibility modeling to shelters and hospital facilities using isochrone-based and zone-based techniques. An example is given in Fig. 6.26, where the accessibility to health facilities is estimated using the results of RDN over all runs.
6.2 CITY OF VIENNA

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. 6.27).

![Fig. 6.27 Electric Power Network input: nodes and sides](image)

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 the data obtained by averaging the results of each run over the total number of runs are reported. 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 10,000) can have different range.

6.2.1 Buildings

Fig. 6.28 and Fig. 6.29 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. 6.30) one can obtain:

\[ \text{Mean annual frequency of exceedance – deaths - 500 years return period earthquake:} \]
\[ 0.7 \times 10^{-3} \times 35402 \text{ (inhabitants)} = 24 \text{ (dead persons)} \]

\[ \text{Moving average – deaths – average over all runs:} \]
\[ 1.1 \times 10^{-4} \times 35402 \text{ (inhabitants)} = 4 \text{ (dead persons)} \]

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. 6.28 Average building collapse (left) and building yielding distribution (right)

Fig. 6.29 Average death (left) and injured (right) distribution
Fig. 6.30 Mean annual frequency of exceedance and moving average (death persons)

From Fig. 6.31:

**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. 6.31 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.

### 6.2.2 Roads

Analysis of the roads damage has shown that blocked as well as unusable ones are concentrated in the proximity of collapsed buildings (Fig. 6.32).

![Fig. 6.32 Average blocked roads (left) and unusable ones (right)](#)

### 6.2.3 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. 6.33).
6.2.4 Electric power network

Also the electric power network results to be slightly damaged as shown in Fig. 6.34.

Fig. 6.33 Pipes broken (left) and non-functional nodes (right)

Fig. 6.34 Average damage on the electric power network nodes
6.2.5 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. 6.35). 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. 6.36. For the sake of simplicity, the values refer to hard rock, realistic ones should account of soil typology in each point of the calculation.

Fig. 6.35 M = 5.4 earthquake 50 km far from Brigittenau district, south-east of Vienna

Fig. 6.36 PGA on rock for the selected event of M = 5.4

Buildings

Fig. 6.37 and Fig. 6.38 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.

![Image](image1.png)  
*Fig. 6.37 Number of buildings collapsed (left) and yield (right) for the selected event of M = 5.4*

![Image](image2.png)  
*Fig. 6.38 Number of deaths (left) and injured (right) persons for the selected event of M = 5.4*

Fig. 6.39 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 manly present.
Fig. 6.39  Number of displaced persons in case of bad weather (left) and good weather (right)

Roads

Road damage is presented in Fig. 6.40. 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.

Fig. 6.40  Blocked roads (left) and unusable ones (right) for the selected scenario
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. 6.41 presents the damage level that affects the electric power network.

![Fig. 6.41 Damage level on the electric power network for the selected scenario](image)

Table 6.1 reports the summary of damage caused by the selected event.

<table>
<thead>
<tr>
<th>Selected event: 278</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M = 5.39</strong></td>
</tr>
<tr>
<td><strong>Hypocenter: 17.0071, 48.0789 Depth: 10 km</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EPN - Broken Transmission Stations</th>
<th>0</th>
<th>BDG - Deaths</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPN - Non functional demands</td>
<td>10</td>
<td>BDG - Injuries</td>
<td>19</td>
</tr>
<tr>
<td>WSS - Broken pipe</td>
<td>0</td>
<td>BDG - Collapse</td>
<td>4</td>
</tr>
<tr>
<td>WSS - Non functional demands</td>
<td>0</td>
<td>BDG - Yield</td>
<td>27</td>
</tr>
<tr>
<td>RDN - Broken</td>
<td>0</td>
<td>BDG - Displaced (GW)</td>
<td>1400</td>
</tr>
<tr>
<td>RDN - Blocked</td>
<td>11</td>
<td>BDG - Displaced (BW)</td>
<td>2411</td>
</tr>
</tbody>
</table>
6.2.6 Interdependency among water supply system and electric power network

Fig. 6.42 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.

![Graph showing weighted connectivity loss for water supply system with and without interdependency](image)

It is shown 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.

6.3 GAS SYSTEM IN L’AQUILA, ITALY

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:

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

(6.1)

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. 6.43 shows the probability of exceedance (complementary cumulative distribution function, ccdf) of the two PIs.

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 \(^1\) and damaged M/R stations were analyzed.

In the following figures (Fig. 6.44 and Fig. 6.45) histograms and scatter plots of these variables with respect to the two performance indicators are shown.

![Graphs showing ccdf and confidence bounds for CL and SR](image)

**Fig. 6.43 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.

\(^1\) Note that pipes do not share the same length.
Fig. 6.44 Histograms of broken pipes in the simulations (top) and scatter plots of PIs with respect to percentage of broken pipes (bottom)
Fig. 6.45 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)

Fig. 6.46 Histograms of broken pipes vulnerable to PGD in the simulations (top) and scatter plots of PIs with respect to percentage of broken pipes vulnerable to PGD (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:

\[
P[X \mid u_1 < PI \leq u_2] = \frac{P[X, u_1 < PI \leq u_2]}{P[u_1 < PI \leq u_2]}
\]  

(6.2)

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 and shown in Fig. 6.47, Fig. 6.48 and Fig. 6.49.
Fig. 6.47 Relative frequency of the number of broken pipes conditional to CL (top) and SR (bottom)
Fig. 6.48 Relative frequency of the number of damaged M/R stations 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 a 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. 6.47 and Fig. 6.49).

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. 6.50 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.
6.4 ROAD NETWORK IN CALABRIA REGION, SOUTHERN ITALY

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.

The analysis results as obtained from a plain MCS of 20,000 runs are presented in the following figures. The chosen number of runs has been shown to yield stable estimates for all considered PIs.
Fig. 6.51 Moving average $\mu$, $\mu+\sigma$ and $\mu-\sigma$ curves for SCL (left) and WCL (right)

Fig. 6.51 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. 6.52, 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. 6.52, 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. 6.53, 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. 6.53, 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. 6.54 the comparison is relative to moving average curves of SCL (left) and WCL (right), while in Fig. 6.55 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 efficacy of ISS and ISS-KM has been tested 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.
6.5 ELECTRIC POWER NETWORK OF SICILY

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

Fig. 6.56 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. 6.57 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. 6.57 MAF curves for CL (left) and SSI (right)
Fig. 6.58 Contour map of expected values of VR

Fig. 6.58 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. 6.59 the comparison is relative to moving average curves of CL (left) and SSI (right), while in Fig. 6.60 it is referred to MAF curves of the same indicators.

Fig. 6.59 Comparison of moving average $\mu$ obtained from MCS, ISS and ISS-KM, for CL (left) and SSI (right)
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.

### 6.6 HOSPITAL FACILITY AND REGIONAL HEALTH-CARE SYSTEM IN ITALY

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, $N_{r+y}$, 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. It is noted 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. 6.61. 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.
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. 6.62. 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.

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. 6.63. 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. 6.63  \( P(HTD \geq HTC) \), for the three region hospitals

6.7 HARBOR OF THESSALONIKI

The analysis results obtained from a plain MCS of 10,000 runs is presented in the following figures. The chosen number of runs has 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 \( P_{la_{max}}=1,032 \) TEUs per day. For the cargo terminal the max value for non-seismic conditions is equal to \( P_{lo_{max}}=43,512 \) 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. 6.64 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-PI/Plmax). Fig. 6.65 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. 6.66. 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. 6.67 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. 6.64 Moving average $\mu$, $\mu+\sigma$, $\mu-\sigma$ curves for TCoH (left) and TCaH (right)
Fig. 6.65 MAF curve for TCoH and TCaH performance loss

Fig. 6.66 MAF curves for TCoH (left) and TCaH (right) for Thessaloniki’s port, with and without interaction with building collapses
Fig. 6.67 MAF curves for TCoH (left) and TCaH (right) for Thessaloniki’s port, with and without interaction with EPN and building collapses.

Fig. 6.68 and Fig. 6.69 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. 6.68 Correlation of damaged cranes to port performance (Pl=TCaH)
Fig. 6.69 Correlation of non-functional electric power distribution substations to port performance (PI=TCaH)

Fig. 6.70 and Fig. 6.71 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, waterfront structures (with the exception of one component) are functional, but the majority of cranes (85% and 88% respectively) are non-functional.

Fig. 6.70 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
D6.8 - Pilot studies and application of SYNER-G methodology

7 Conclusions

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.

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 (shakfields method, Weatherhill et al. 2011) and all systems are analyzed for each event. 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, regional hospitals system in Italy). This is 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 dependencies. 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.
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