SYSTEMIC SEISMIC VULNERABILITY AND RISK ANALYSIS FOR BUILDINGS, LIFELINE NETWORKS AND INFRASTRUCTURES SAFETY GAIN
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SYNER-G is a European collaborative research project focusing on systemic seismic vulnerability and risk analysis of buildings, transportation and utility networks and critical facilities. The originality of the project is the **systemic approach of vulnerability and risk assessment of complex interacting systems**. The whole methodology is implemented in an **open source software tool** and is validated in selected **case studies**.

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

The methodology and software tools are validated in selected sites and systems in urban and regional scale: city of Thessaloniki (Greece), city of Vienna (Austria), harbour of Thessaloniki, gas system of L’Aquila (Italy), electric power network, roadway network and hospital facility in Italy. Representative results are presented hereinafter.
SYNER-G is integrated across different disciplines with an internationally recognized partnership from Europe, USA and Japan. The 14 participants in the consortium represent a variety of organizations, from universities and academic institutions to research foundations and SMEs.

The objectives and the deliverables are focused to the needs of the administration and local authorities, which are responsible for the management of seismic risk, as well as the needs of the construction and insurance industry.

Fig. 1. SYNER-G workflow
Main goals of SYNER-G are:

i) to elaborate appropriate, in the European context, fragility relationships for the vulnerability analysis and loss estimation of all elements at risk;

ii) to develop social and economic vulnerability relationships for quantifying the impact of earthquakes;

iii) to develop a unified methodology, and tools for systemic vulnerability assessment accounting for all components exposed to seismic hazard, considering interdependencies within a system unit and between systems;

iv) to validate the methodology and the proposed fragility functions in selected sites and systems and to implement in an appropriate open source software tool.
The conceptual basis and general principles of a unified methodology to evaluate systemic vulnerability have been developed in this work package. An innovative methodological framework has been proposed in Tasks 2.1 and 2.2 for the assessment of the physical as well as socio-economic seismic vulnerability at the urban/regional level. The built environment has been modelled according to a detailed taxonomy into its component systems, grouped into the following categories: buildings, transportation and utility networks, and critical facilities (as defined in Task 2.3). The framework encompasses in an integrated fashion all aspects in the chain that go from the regional hazard (investigated in Task 2.4) to fragility assessment of components to the social impacts of an earthquake, accounting for all relevant uncertainties within an efficient quantitative simulation scheme, and modelling interactions between the multiple component systems in the taxonomy. The use of remote sensing for an improved characterisation of the built environment and its vulnerability has also been considered, as described in Task 2.5.

Task 2.1: Development of the general methodology of the systemic vulnerability accounting for all elements at risk, including interdependencies

The primary focus of Task 2.1 was the development of a comprehensive methodology for the analysis of systemic vulnerability for a set of inter-dependent infrastructures. This task has been critical for the practical implementation of the outputs from the other SYNER-G components, and it was therefore necessary that the task was completed by the 18 month stage of the project, prior to the application of the case studies. A systemic approach for the analysis of interdependent infrastructural systems has been developed and a prototype software was created and tested.
The general methodology, described in detail in Deliverable 2.1, addresses many key issues that require a substantial degree of consideration:

i) The establishment of a detailed taxonomy of each infrastructure within a number of connected infrastructural systems. This taxonomy contains a detailed description of each system and its components, and also formalises the general nomenclature intended for use within the project.

ii) The creation of a model of the infrastructure that is formalised within an object-oriented framework. This describes the inter- and intra-dependencies between the various systems and components that have been outlined within the general taxonomy. The object-oriented characterisation of the infrastructure provides a clear basis for implementation in the analysis software.

iii) The integration of a methodology for quantitative analysis of the uncertainties at various levels of the systemic analysis. This includes the seismic input (described in more detail in Task 2.4), the physical damageability of the components of the infrastructure (as modelled by the fragility functions defined in work package 3), the functional consequences of the system for a given degree of physical damage at the component level and the socio-economic consequences of the physical damage. The analysis of uncertainty addresses both aleatory and epistemic causes, the latter becoming increasingly significant for systemic performance.

iv) The definition and categorisation of performance indicators for systemic risk. These are considered at the level within the infrastructure in which they are implemented. This corresponds to three categories: component, system and infrastructure.

v) An integrated evaluation of both physical and socio-economic performance indicators.

The prototype software (OOFIMS) has been developed using Object-Oriented Matlab. This platform has been adopted as it enables rapid implementation and testing of methodologies, whilst clearly maintaining the object-oriented framework of the model infrastructure. This software is not open source; however, it provides a clear illustration of the capabilities of the methodology, in such a manner that can be translated into other computational interfaces without reconfiguration of the model infrastructure.
Task 2.2: Methods to consider socio-economic issues and evaluation of losses

The socio-economic modelling approach is based on multi-criteria decision support, which integrates social vulnerability into the physical system modelling approaches to provide decision makers with a dynamic platform to capture post-disaster emergency shelter demand and health impact decisions. The general methodology for integrating the physical and socio-economic performance indicators was identified within this work-package, and this was then further developed in Work Package 4.
Task 2.3: Typology definitions of European Elements at Risk (including data collection, archiving and processing)

The main objective of this task was to identify the data required in order to define the common characteristics of structural and non-structural elements within typical European systems. These have then been used to propose a harmonised template for data collection. This task underpins concurrent work undertaken in work package 3 to define the fragility functions for the structural and non-structural elements within each system. A comprehensive literature survey of existing typology and taxonomy definitions and classifications for elements at risk within each system were compiled. Focus was primarily directed toward the EUROSTAT classification of construction types in Europe. Further use was made of other existing typology definitions including EMS 98, HAZUS, Risk-UE and PAGER. The review of data collection methods included census, owner/operator data, ground surveys, remote sensing and aerial photography.

The second stage of this task focused on collection and classification of inventory data. For this purpose, comprehensive means of archiving within a harmonised template were developed. These assumed the form of Microsoft Excel spreadsheets, GIS-based applications and a standalone toolbox (implemented in Matlab). A general report to provide guidelines for typology definitions was developed, and the main output of this task has been compiled in the form of Deliverable 2.11.

Task 2.4: Seismic scenarios

The definition of seismic scenarios requires the development of a clear methodology for characterising the hazard input in a manner that is appropriate for application to the analysis of multiple infrastructures. For novel applications such as this, conventional approaches for the estimation of seismic hazard are insufficient to characterise the properties of ground motion that are most relevant for each infrastructure.

This task was divided into two sub-tasks. The first related to the identification of the most efficient measures of ground motion measurement for each infrastructure or element within each infrastructure. For this task an extensive literature review was undertaken to identify initially the best means of determining the most appropriate intensity measure for a given element, and then identifying the most efficient intensity measure for each element or collection of elements within an infrastructure (see Deliverable 2.12).
For the definition of the seismic input itself, a Monte Carlo simulation methodology was developed, which has been integrated within the general methodology for systemic vulnerability analysis and the aforementioned OOFIMS prototype software. The methodology, the so-called “shakefield” approach, aims to take into account both the spatial correlation in ground motion for each intensity measure, as well as the cross-correlation and spatial cross-correlation between multiple intensity measures. This is a significant development that allows for a more direct generation of the ground motion inputs that have been identified as most efficient for each infrastructure. The spatial correlation and cross-correlation is captured via co-simulation of correlated fields of Gaussian variates, representing the residual term of the ground motion prediction equation (GMPE).

Fig. 4. Overview of the “shakefield” methodology, including the attenuation of ground motion from an event and the generation of correlated Gaussian fields as a means of simulating spatial correlation and cross-correlation in the GMPE residual term.
This task has led to several significant developments in seismic input modelling for risk analysis that can be found in Deliverable 2.13:

i) Creation of an adaptable methodology for generating multiple fields of ground motion, taking into account spatial correlation and cross-correlation

ii) Development of spatial correlation and cross-correlation models based on European strong motion records. This is undertaken addition to a review of existing correlation models, and the results interpreted in the context of models derived from non-European data

iii) Extension of the “shakefield” methodology to incorporate geotechnical elements of seismic hazard, including site amplification, liquefaction, co-seismic slope displacement and transient strain. This extension is based upon the template developed within the HAZUS software, with its corresponding probability definitions now interpreted in a stochastic context. Several elements of the HAZUS model that relate the expected permanent ground displacement to the strong shaking, have been updated using recent empirical models that better constrain uncertainty in these terms. These new models are also implemented in a stochastic context.

Task 2.5: Remote sensing for systemic vulnerability analysis

This task has focused on two aspects relating the use of remote sensing for systemic vulnerability analysis. As such, the task was divided into two subtasks, the first assessing the use of remote sensing for inventory and data capture, the second considering the potential for vulnerability assessment from optical imagery. Available census and geo-data for the case study regions of Thessaloniki and Vienna has been collected for the integration of remote sensing and GIS data. The geo-data included information relating to administrative boundaries, demographics, land use, road network, building blocks, building footprints, building inventory and satellite images. These were then harmonised into a geodatabase. Testing of methodologies for extraction of information from high resolution remote sensing were then carried out, including the identification of planar indicators for describing building complexity, aggregation and proximity to roads.

An initial review of exiting approaches and techniques to extract urban information from optical satellite imagery is described in Deliverable 2.16. These considered both geometric parameters, i.e. those that provide direct information about the building’s geometry, and inferred parameters, which are determined by combining geometric information with ancillary data (possible derived by other means).
The use of radar reflectivity maps as a possible means of deriving information needed to determine vulnerability factors in earthquake prone regions has also been undertaken. Two types of vulnerability were considered: 1) vulnerability of people in the emergency phase, and 2) physical vulnerability of buildings. For this purpose COSMO/SkyMed Spotlight images (at 1 m resolution) were obtained from the Italian Space Agency, targeted at specific sites Messina, Italy, and Vienna, Austria. One possible approach to assess vulnerability in the emergency phase was the use of optical satellite imagery as part of an automated urban road extraction network, to rapidly map viable escape and emergency transportation routes after a seismic event, as shown below for Vienna.

![Road segments (red) superimposed over an optical satellite image of Vienna centre](image)

Fig. 5. Road segments (red) superimposed over an optical satellite image of Vienna centre

For the assessment of physical building vulnerability, remote sensing techniques have been tested as a means of deriving building height over urban regions. Building heights were obtained from side-looking radar images, before considering the possible issues involved in height extraction from radar imagery. To derive heights from radar images, the commercial software package Paneidos (www-paneidos.eu) was used, with manual intervention required to visually locate building extremities. An additional cross-reference experiment was also undertaken, using optical imagery to more clearly define distinctive characteristics of buildings that result in correct or incorrect estimates of parameters relevant to vulnerability (e.g. number of floors).
WP 3: Fragility Functions of Elements at Risk

The WP3 activities deal with the development of fragility curves/functions for all the system elements based on the taxonomy/typology that is established in the framework of WP2. A literature review on the typology, the fragility functions (analytical/empirical/expert judgment/hybrid), damage scales, intensity measures and performance indicators is performed for all the elements in WP3.

The fragility functions are based on either new analyses or collection/review of the results that are available in the literature. In some cases, the selection of the fragility functions is based on validation studies using damage data from past and recent earthquakes, mainly in Europe. The damage and serviceability states are defined accordingly. Appropriate modifications are made to the selected fragility functions in order to satisfy the distinctive features of the adopted taxonomy. In many cases new fragility functions are developed based on numerical solutions or by using fault tree analysis together with the respective damage scales and serviceability rates in the framework of European typology and hazard.

A fragility function manager tool is developed for buildings and bridges and is connected with the SYNER-G software platform. This tool is able to store, visualize, harmonise and compare a large number of fragility functions sets (Fig. 6).

Fig. 6. Fragility function manager tool
BUILDINGS

The main typologies of buildings in Europe are identified, and by focusing on reinforced concrete and masonry buildings, the existing fragility functions are reviewed with the objective of homogenizing the existing building types using a new taxonomy, called the SYNER-G taxonomy (Fig. 7). The main outcome of these studies is a set of fragility functions, with their associated uncertainties, for the common typologies present in Europe.

Fig. 7. Pie charts exposing the percentages about the methodology used to develop fragility function for (a) reinforced concrete buildings and (b) masonry buildings

Fig. 8. Mean fragility function for (a) limit state yielding curve and (b) limit state collapse curve for a reinforced concrete building typology
In total, 415 fragility function sets for buildings are collected as part of the project. Additionally, new numerically-derived fragility curves are developed for certain building types. A main objective is to look at how fragility functions from the numerous existing studies compare, and to quantify the epistemic uncertainty. In Fig. 8 the mean fragility function is shown on top of the individual fragility functions for a reinforced concrete structure with moment resisting frame buildings, mid-rise, seismically designed, bare, non-ductile.

**ELECTRIC POWER SYSTEMS**

The components of the electric power system can be grouped on the basis of four different analysis levels of the network: Network/Station/Distribution-system/Substation’s component. A distinction between micro- and macro-components is made, which is useful in terms of reliability analysis when the approach to network modelling is capacitive -that is, power flows are computed - and the internal logic of substations is modelled- that is, partial functioning, meaning continued service with reduced power flow, is accounted for.

The considered macro-components are: (1) Line without transformer, (2) Bars-connecting line, (3) Bars, (4) Autotransformer line.

The existing fragility functions for the water and waste-water components have been reviewed. For pipes the empirical fragility curves of O’Rourke and Ayala (1993) for the case of wave propagation and Honneger and Eguchi (1992) for the case of permanent ground deformation are proposed. The selection is based on a validation study that has been performed for the 1999 Düzce and the 2003 Lefkas earthquakes. The fragility curves for all components are summarized in Table 1.

### Table 1. Summary of proposed fragility functions for water and waste-water systems

<table>
<thead>
<tr>
<th>Element</th>
<th>Methodology</th>
<th>Classification</th>
<th>Intensity measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water sources</td>
<td>SRMLIFE, 2003-2007</td>
<td>Anchored/ unanchored components</td>
<td>PGA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seismic design of building</td>
<td></td>
</tr>
<tr>
<td>Water treatment plants</td>
<td>SRMLIFE, 2003-2007</td>
<td>Anchored components</td>
<td>PGA</td>
</tr>
<tr>
<td>Pumping stations</td>
<td>SRMLIFE, 2003-2007</td>
<td>Anchored/ unanchored components</td>
<td>PGA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seismic design of building</td>
<td></td>
</tr>
<tr>
<td>Storage tanks</td>
<td>ALA, 2001</td>
<td>Anchored R/C tanks at grade</td>
<td>PGA, PGD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unanchored R/C tanks at grade</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open reservoirs with or without seismic design code</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Buried R/C tanks</td>
<td></td>
</tr>
<tr>
<td>Canals</td>
<td>ALA, 2001</td>
<td>Unreinforced liners or unlined reinforced liners</td>
<td>PGV, PGD</td>
</tr>
<tr>
<td>Water and Waste water pipelines</td>
<td>O’Rourke and Ayala (1993)</td>
<td>Pipe material</td>
<td>PGV, PGD</td>
</tr>
<tr>
<td></td>
<td>Honneger and Eguchi (1992)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water and Waste water tunnels</td>
<td>Same as roadway tunnels</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seismic design of building</td>
<td></td>
</tr>
<tr>
<td>Lift stations</td>
<td>SRMLIFE, 2003-2007</td>
<td>Anchored/ unanchored components</td>
<td>PGA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seismic design of building</td>
<td></td>
</tr>
</tbody>
</table>
GAS AND OIL NETWORKS

These systems consist of a number of critical facilities, the transmission and distribution network made of pipelines and supervisory sub-system (Table 2).

<table>
<thead>
<tr>
<th>Element</th>
<th>Methodology</th>
<th>Classification</th>
<th>Intensity measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipelines</td>
<td>ALA (2001)</td>
<td>Pipe material, joint type, soil type and pipe diameter</td>
<td>PGV</td>
</tr>
<tr>
<td></td>
<td>Empirical</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ALA (2001)</td>
<td>Pipe material, joint type</td>
<td>PGD</td>
</tr>
<tr>
<td></td>
<td>Expert judgment/</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Empirical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage tanks</td>
<td>HAZUS (2004)</td>
<td>Anchored or unanchored</td>
<td>PGA</td>
</tr>
<tr>
<td>Processing</td>
<td>Generic station, Anchored or unanchored components</td>
<td>PGA</td>
<td></td>
</tr>
<tr>
<td>facilities</td>
<td>SRMLIFE (2007)</td>
<td>Greek typology</td>
<td>PGA</td>
</tr>
</tbody>
</table>

TRANSPORTATION INFRASTRUCTURES

Transportation systems include roadway, railway and subway networks, port and airport systems and infrastructures. Each system is a complex network of various components like bridges, roads, tunnels, embankments, retaining walls, slopes in case of roadway system or wharfs, cranes, buildings, utility systems, tanks and other in case of harbour.
ROADWAY AND RAILWAY ELEMENTS

The main typological features of roadway/railway components are classified and the existing methodologies are reviewed together with the damage states definitions, intensity measures and performance indicators of the elements. Empirical curves are proposed for tunnels in rock and road pavements. The curves for roadway pavements are validated based on damage data from recent earthquakes. Using numerical modelling of earthquake response, new fragility curves are developed for tunnels in alluvial, road/tracks on embankments, road/tracks in trenches and bridge abutments based on PGA as the intensity measure (Fig. 10).

Fig. 10. Examples of numerical fragility curves for abutment, soil types C (a) and D (b)
A tool for fast fragility analysis of regular bridges was developed. It allows for free or constrained transverse translation at the abutments and for continuous deck or one with intermediate joints. The deck-pier connection may be monolithic, through elastomeric bearings or a combination of the two. The tool performs design of simplified models according to Eurocodes 2 and 8. Following the assessment procedure of EC8’s Part 3 for the two horizontal components of the seismic action, it produces fragility curves for piers, bearings and also for the deck horizontal deformation (Fig. 11).

Fig. 11. Fragility curves for six-span bridge with continuous deck supported on bearings and constrained transverse translation at the abutments, designed to EC2 (a) or EC8 (b)
Poor linkages between damage to physical systems and resultant social consequences remain a significant limitation with existing hazard loss estimation models. One of the aims in SYNER-G is to develop a unified approach for modelling social losses caused by earthquake damage which integrates social vulnerability into the physical systems modelling approaches. Contributing to the challenge of integrating social vulnerability with physical damage/performance models is the fact that social vulnerability is a fundamentally relative phenomenon and not something that can be directly observed and measured. The integrated approach proposed in SYNER-G provides a framework to link the degree of damage and performance of physical systems to vulnerabilities and coping capacities in society to assess: (1) Impacts on displaced populations and their shelter needs, and (2) Health impacts on exposed populations and their health-care needs.

The shelter need model in SYNER-G provides a methodology and indicator based system to obtain shelter demand as a function of the habitability of buildings (defined by a households tolerance to the loss of power, gas and water for different levels of building damage and weather conditions); and a set of key socio-economic indicators influencing a population to leave their homes and seek or not seek public shelter. Accordingly, the shelter model simulates a households' decision-making and considers physical, socio-economic, climatic and spatial factors in addition to modelled building damage states. The integrated shelter needs model developed in SYNER-G is based on a multi-criteria decision theory (MCDA) framework which allows the bringing together of parameters influencing the physical inhabitability of buildings, with social vulnerability (and coping capacity) factors of the at-risk population to determine as well as external factors to determine the desirability to evacuate and seek public shelter. As shown in Fig. 12, the multi-criteria framework can be described schematically as composed of the two main criteria: overall population at risk of being displaced after an earthquake (DPI) and the proportion of this population likely to seek public shelter (SSI). Subsequently, the total demand for public shelter for a particular location (i.e., city district) can be described as a product of the population at risk of being displaced (related to the occupants in uninhabitable buildings and their desire to evacuate or not) and a set of indicators determining the population likely to seek public shelter.
To operationalize the shelter model, appropriate indicators from the EU Urban Audit Database have been selected using principal component analysis combined with expert judgment. Vulnerability factors deduced from the EU Urban Audit have been validated by applying the model using data from the M 6.3 earthquake that struck L’Aquila, Italy in April 2009. Fig. 13 shows how the modelling approach can be used to capture the actual shelter demand conditions (given as the observed number of people in shelter camps normalized by total population in different Mixed Operations Centres (COM) which had the overall coordinating role in their own territories for all rescue and shelter provision operations after the L’Aquila earthquake.
Similarly, the health impact model presents a new method for integrating social vulnerability in modelling health impacts caused by earthquake damage. Although social vulnerability is recognized as a key component for the consequences of disasters, social vulnerability as such, is seldom linked to quantitative frameworks which provide direct impact on emergency health care services. Yet, there is a consensus that factors which affect vulnerability and post-earthquake health of at-risk populations include demographic characteristics such as age, education, occupation and employment and that these factors can aggravate health impacts further. Similarly, there are different social influences on the performance of health care systems after an earthquake both on an individual as well as on an institutional level. To link social impacts of health and health-care services to a systemic seismic vulnerability analysis, a multi-criteria decision model has been developed and appropriate social indicators for individual health impacts and for health care impacts were identified based on literature research, and tested using available European statistical data. The results were used to develop a health impact model that describes the processes and links between socio-demographic, environmental, epidemiological and health behaviour parameters to increased short-term health impacts. Furthermore, healthcare systems parameters are integrated in a healthcare capacity model to assess secondary impacts on the overall health care delivery to the affected population.
Based on the general methodology developed in WP 2, this work package is devoted to the specification of the various features composing the SYNER-G approach for each of the considered systems. The main characteristics that define each system can be broken down into the following:

- **Taxonomy** of the components within the system;
- **Solving algorithms** used to assess the system’s performance;
- Nature of the **interactions** with components from other systems.

**Taxonomy of components within each system**

Following the framework of the general SYNER-G methodology, each class of systems is composed of sub-classes that are used to describe the various types of components, based on the geographical extent and their function within the system:

- **Cell classes** are used to define inhabited areas (i.e. Buildings System) and contain information on buildings typologies, population or soil occupation policy.

- **All network-like systems** (i.e. Water Supply, Electric Power, Gas Network and Road Network) contain two types of sub-classes (Edges and Points), which are further sub-divided in specific classes, according to the role played by the component within the system: network nodes can be stations, pumps, reservoirs, sources, distribution nodes, etc.

- For **critical facilities** such as components of the Health-Care System, they are modelled as point-like objects.

Each of the sub-classes is specified with their characteristic attributes and methods, depending on the type of system considered. For instance, initial properties of the objects may include geographic location, area, length, soil type, typology, associated fragility, capacity, connectivity with other components (for networks), etc. Once the simulation is running, the specific methods...
update the object properties, such as damage states, losses within each cell or remaining connectivity.

![Diagram of Road Network System]

Fig. 14. Example of a specified UML (Unified Modelling Language) diagram for the Road Network System

**System evaluation and performance indicators**

The way the performance of each system is assessed is also addressed in the work package. Three main types of solving algorithms are considered in the SYNER-G approach:

i) **Connectivity analysis**: this approach removes the damaged components from the network and it updates the adjacency matrix accordingly, thus giving the nodes or areas that disconnected from the rest of the system. This approach is used for all utility networks (water, electricity, gas) and the road transportation system.

ii) **Capacitive analysis**: for utility networks, graph algorithm can be used to optimize capacitive flows from sources (e.g. generators, reservoirs) to sinks (i.e. distribution nodes), based on the damages sustained by the network components (from total destruction to slight damages reducing the capacity).

iii) **Fault-tree analysis**: this type of approach aims to evaluate the remaining operating capacity of objects such as health-care facilities. The system is broken up into structural,
non-structural or human components, each one of them being connected with logic operators.

Performance indicators, at the component or the system level, depend on the type of analysis that is performed: connectivity analysis gives access to indices such as the connectivity loss (measure of the reduction of the number of possible paths from sources to sinks). On the other hand, capacitive modelling yields more elaborate performance indicators at the distribution nodes (e.g. head ratio for water system, voltage ratio for electric buses...) or for the whole system (e.g. system serviceability index comparing the customer demand satisfaction before and after the seismic event).

Interdependencies

Three types of interactions between systems are considered within SYNER-G:

i) “Demand” interactions: they correspond to a supply demand from a given component to another system. For instance, the presence of densely populated cells in the vicinity of a given distribution node (e.g. from a water supply or electric power system) will generate a substantial demand on the supply system. Another example could be the number of casualties that will put a strain on the treatment capacity of health-care facilities.

ii) Physical interactions: they are associated with exchanges of services or supplies between systems, like the supply of potable water to inhabited cells, the supply of transportation capacities by roads or the supply of power to various network facilities (e.g. water pumps) by electric generators.

iii) Geographical interactions: they are involved when two components are located in the same area and when the damage of one of them is directly influencing the physical integrity of the second one. For instance, the collapse of buildings in city centres can induce the blockage of adjacent roads due the debris accumulation.
The interactions between systems that are treated in the frame of SYNER-G are listed in the table below:

**Table 3. Interactions between systems. D: Demand, P: Physical and G: Geographical interactions**

<table>
<thead>
<tr>
<th>Impacts</th>
<th>BDG</th>
<th>EPN</th>
<th>WSS</th>
<th>GAS</th>
<th>RDN</th>
<th>HBR</th>
<th>HCS</th>
<th>FFS</th>
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<tbody>
<tr>
<td>Buildings</td>
<td>BDG</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
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<td></td>
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<tr>
<td>Power</td>
<td>EPN</td>
<td>P</td>
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<td>RDN</td>
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It should be noted that the “demand” interactions are considered as static, since they are estimated only once, in order to avoid the presence of any feedback loops that would introduce dynamic systems, which are left of the SYNER-G scope. As a result, this table of interdependencies governs the order in which each system has to be computed during the simulation runs, in order to maintain a straightforward analysis scheme.
GENERAL DESCRIPTION

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

In the present case study, 5 seismic zones are selected for the seismic hazard input, obtained by SHARE European research project (Fig. 15).

A Monte Carlo simulation (MCS) has been carried out (10,000 runs) based on the methods and tools developed in SYNER-G (see WP2, WP3, WP5, WP7). The case study includes: building stock (BDG), road network (RDN), water supply system (WSS), electric power network (EPN). For each system, selected Performance Indicators (PI’s) are calculated based on the estimated damages and functionality losses of the different components. Specific interdependencies 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). The overall performance of each network is expressed through the Mean Annual Frequency (MAF) of exceedance and the moving
average $\mu$ and moving standard deviation $\sigma$ of the PIs. Thematic maps showing the distribution of expected damages/losses can be produced for a selected event. Moreover, the significant elements for the functionality of each system can be defined through correlation factors to the system PIs. As an example, the expected damages and losses for a characteristic event of $M=6.0$ with epicenter north-west of the city ($R=12\text{km}$) are presented in the following paragraphs (Fig. 16).

![Fig. 16. Characteristic event (M=6.0, R=12km)](image)

**BUILDINGS (BDG)**

The building inventory covers the entire municipality of Thessaloniki; it comprises 2,893 building blocks with 27,738 buildings, the majority of which (25,639) are reinforced concrete (RC) buildings, while the rest (2,099) are masonry buildings. The inventory includes information about material, code level, number of storeys, structural type and volume for each building. The information is given in building block level. The database is based on previous project results (Kappos et al. 2008) and has been expanded within SYNER-G using remote sensing techniques. The study area comprises 20 Sub-City Districts (SCD) as they are defined by Eurostat through the European Urban Audit (EUA) approach. The total population in this area is 376,589 inhabitants.

Three-dimensional finite element analysis with a nonlinear biaxial failure criterion was used to derive fragility curves for masonry buildings that consider in-plane and out-of-plane failure (Fig. 17). Fragility curves for RC buildings that account for shear failure and consider model uncertainties and the scatter of material and geometric properties were produced following the assessment method of Eurocode 8. Results for wall-frame buildings are shown in Fig. 18, where the effect of design codes is evident.
Fig. 17. Four-storey masonry building w/flexible floors: fragility curves (a); analysis results showing out-of plane damage (b)

Fig. 18. Fragility curves for low-rise wall-frame buildings in Thessaloniki designed with low-level (a), medium-level (b) and high-level (c) seismic code

**Results**

The study area is divided in cells and the expected losses are calculated for each cell of the grid. A representative example of estimated losses for the characteristic event of Fig.16 (M=6.0, R=12km), in terms of casualties and building damage, is shown in Fig. 19. The total number of deaths estimates is located in the area of expected building collapses, both located at the city area closest to the earthquake epicentre. A large number of yield buildings is expected at specific cells towards the other end of the city.
Fig. 19. Distribution of estimated casualties (deaths, injuries) and damages (collapsed & yielded buildings) in cells of the study area for a characteristic event.
ROAD NETWORK (RDN)

The road network for the case study is composed of 594 nodes and 674 edges. The nodes are subdivided into 15 external nodes, 127 Traffic Analysis Zone (TAZ) centroids and 452 simple intersections. The RDN is modelled as a directed graph and all edges have a travelling direction. For this particular network, 495 edges are two-ways roads and 179 are one-way roads. Other information include the width of the road, the distance from buildings, the classification (principal, secondary), the capacity and flow speed. Edges, that are the only vulnerable components in the network, are subdivided into road pavements and bridges. Direct (physical) and indirect failures are considered: 1) bridge damage due to ground shaking (peak ground acceleration) or road damage due to liquefaction (permanent ground displacement; 2) road blockage due to collapsed buildings; 3) road blockage due to collapsed bridges (overpasses).

Analytical fragility curves were developed for specific bridges in the Thessaloniki study area, based on the available information about their geometry, materials and reinforcement. Older bridges are likely to experience damage for low to medium levels of earthquake excitation (e.g., Fig. 20a). On the other hand, modern bridges are markedly less vulnerable (e.g., Fig. 20b).

Fig. 20. Fragility curves for (a) a bridge with the deck supported on bearings, constructed in 1985 and (b) an overpass with monolithic deck-pier connection, constructed in 2003.
The network performance is analyzed in terms of pure connectivity with reference to selected performance indicators (PI’s). In particular, the Mean Annual Frequency (MAF) of exceedance of Simple Connectivity Loss (SCL) and Weighted Connectivity Loss (WCL) are evaluated based on the simulation results (10,000 runs) (Fig. 21). Fig. 22-23 show the damages in the network for a characteristic event with $M=6.0$. Road blockages due to building collapses, road damages due to ground failure (liquefaction), blockage by overpass bridges and bridge damages are evaluated.

Fig. 21. MAF curve for SCL and WCL

Fig. 22. Road blockages due to building collapse for a characteristic event.
Fig. 23. Road damages due to ground failure (liquefaction), blockage by overpass bridges, and bridge damages for a characteristic event. Overall performance of the network: 10 - 13% loss of connectivity.

WATER SUPPLY SYSTEM (WSS)

Thessaloniki’s main potable water system is comprised of about 350 km of pipes. The current inventory database includes several attributes such as location, diameter, material, age, operating area, supplied tank, type, depth, length, joint type and history of failures, where these data are available.

Due to the complexity of the system, along with the fact that in several cases the system is not known, a simplified model for Thessaloniki’s WSS is used for the analysis. The WSS for the case study is comprised of 477 nodes and 601 edges. The nodes are subdivided in demand nodes, pumping stations and tanks; the latter considered as water sources for the system. Edges include only pipelines (both transmission and distribution). The interconnections between electric power substations and pumping stations are identified.
Results

A pure connectivity analysis is performed with and without interdependency of pumping stations to electric power supply. The WSS performance is defined through the Weighted Connectivity Loss (WCL). Fig. 24 illustrates the Mean Annual Frequency (MAF) curve for the WCL. It can be seen that for 500 years return period of the PI (i.e. 0.002 probability of exceedance), the connectivity loss of the system is 1.4% and 0.7%, with and without interaction to EPN respectively. The expected system performance for a characteristic event is shown in Fig. 25, in terms of broken pipes (2.1% of the total network length), not functional pumping stations and not-connected demand nodes.

![Fig. 24. MAF curve for connectivity loss of WSS, with and without interaction with EPN considered in the analysis.](image)
Fig. 25. Water supply system damages for a characteristic event. Overall performance of the network: 1.2% loss of connectivity.
ELECTRIC POWER NETWORK (EPN)

The electric power transmission system is considered in the analysis. The network for the case study is composed of 30 nodes and 29 edges. The nodes are sub-divided into 1 generator, 8 transmission substations and 21 demand nodes (pumping stations of WSS). Transmission substations are the only vulnerable components. Edges are non-vulnerable transmission lines (underground and overhead) connecting the generator with the transmission substations and the transmission substations with the demand points.

Results

The network performance is analyzed in terms of pure connectivity. The expected system performance for a characteristic event is shown in Fig. 26, in terms of not functional transmission stations and not-connected demand nodes. For the specific event, there is 38% loss of connectivity through the entire system. The network components with profound effect on the overall system performance are characterized by high correlation levels to the PI (Fig. 27).

Fig. 26. Electric power network losses for a characteristic event. Overall performance of the network: 38% loss of connectivity.
Fig. 27. Level of correlation of not-functional transmission substations and system connectivity loss.
SOCIO-ECONOMIC 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 (see WP 4). In particular, a Shelter Needs Index (SNI) is estimated for each one of the 20 Sub City Districts (Fig. 28) 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).

Fig. 28. Shelters needs index (SNI) for Thessaloniki SCDs
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. 29, where the accessibility to health facilities is estimated using the results of RDN over all runs.

Fig. 29 Accessibility to hospitals for Thessaloniki SCDs (zone based technique)
Vienna City

Population: 1,697,982 people
Total Area: 414.89 km²
Number of Districts: 23
Land Usage: Buildings (12%)
  - Gardens and Parks (28%)
  - Transportation (13%)
  - Forest (18%)
  - Agricultural Usage (15%)
  - Water (5%)

Test Area

Population: 84159 people
Total Area: ~ 1 km²
Building Usage: Residential

Fig. 30. (a) Overview of the Vienna city, (b) close-up view of the test area.
The test area is located in the 20th district of Vienna. The database of the area consists of ~600 buildings, where about 85% of them are residential buildings. Out of these 85% around 80% are typical “Gründerzeithäuser”, which are masonry buildings constructed between 1890 and 1960. The database contains all lifelines, networks and systems relevant for such a case study. In addition the database on the buildings is very detailed, each building was characterised through a building identification procedure (Fig. 31).

![Building Identification Procedure](image)

**Fig. 31. Building Identification Procedure**

The case study will be analysed with two software modules. One of these modules is the OOFIMS-module. The computation is done in Matlab, but the software is completely implemented in the platform. The scenario in Vienna has been analysed with respect to buildings, water and road network. Additionally the systemic approach can be tested. The figures show some typical results of the software.

![Classification of buildings through usage](image)

**Fig. 32. Example classification of buildings in terms of usage functions**
While Fig. 33 shows the typical cell structure, in which the software computes all the necessary information on a test case, Fig. 34 shows the same information already computed in Sub City Districts. A connection module sums up the information on the cells and displays it in a GIS-format.

The second software module is the original development of MAEviz. A scenario earthquake is computed, which derives the hazard values for each point on the map. In SYNER-G a new routine was developed mapping the correct European fragility functions to the newly developed Taxonomy. This fragility mapper is another plug-in in the software. In future development every region in the world can implement its own fragility mapping and taxonomy. EQvis can then compute damages, repair cost, direct economic losses, non-structural and content loss, etc. for each information point on the map, e.g. a building point. EQvis creates tables with all this information which makes filtering, displaying, etc. very easy.
Port transportation systems, whose primary function is to transport cargos and people, contain a wide variety of facilities for passenger operations and transport, cargo handling and storage, rail and road transport of facility users and cargoes, communication, guidance, maintenance, administration, utilities, and various supporting operations. The elements existing within port facilities can be classified as following:

- Waterfront structures.
- Cargo handling and storage components.
- Infrastructures.
  - Buildings (sheds and warehouses, office buildings, maintenance buildings, passenger terminals, traffic control buildings).
  - Utility systems (electric power system, water system, waste-water system, natural gas system, liquid fuel system, communications system, fire-fighting system).
  - Transportation infrastructures (roadway system, railway system, bridges).

The main characteristic of ports’ complex systems is the multiple interactions existing within their elements and with the external supplying or/and supplied systems and infrastructures. The ports’ functionality is dependent on the functioning of each system/ component, taking also into consideration the interactions between them. Moreover, port performance cannot normally be assessed on the basis of a single value or measure.

For the assessment of the systemic vulnerability of harbors within SYNER-G, port operations are simulated, as long as the derivation of performance in case of perturbations, such as the occurrence
of an earthquake event. Simulation models have been developed for the movement of cargos (containers and bulk cargo). The assumption of discrete port functions per terminal is made. The elements studied include the piers and berths (waterfront) and cargo handling equipment.

The main Performance Indicator (PI) used is the total cargo handled in a pre-defined time frame per terminal and for the whole port system. The simulated interdependencies include the interactions between cargo handling equipment and Electric Power Network (EPN), as well as the road closures due to potential building collapses. In this case, the cargo movements 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. 36). Finally, annual rates of exceedance for all PIs are evaluated from a given number of events sampled from the seismic hazard.

![Fig. 36. Functionality simulation of port facilities.](image)

The developed model for the assessment of the systemic vulnerability of harbors is applied in Thessaloniki’s port (Northern Greece). Thessaloniki’s 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. The geographic representation of Thessaloniki’s port waterfronts, cranes and electric power supply system is shown in Fig. 37.

A Monte Carlo Simulation with 10,000 runs is performed. System Performance Indicators (total number of containers handled, total cargo handled, total number of containers’ movements, total cargo movements) are estimated, considering also for all intra and inter-dependencies. For the seismic hazard, five zones representing the areas seismicity are used, obtained by SHARE European
research project (see application to Thessaloniki urban area). Some representative results are provided in the following figures.

Fig. 37. Geographic representation of Thessaloniki’s port components.

Figures 38 and 39 illustrate the moving average over all runs and the Mean Annual Frequency curve for the normalized Performance Indicator TCoH [Total number of Containers Handled (loaded and unloaded) per day].

The results for a characteristic event, in terms of cranes and waterfronts functionality, are given in Fig. 40. For the specific event, with $M=6.1$, there is 74% loss of total number of containers handled per day and 40% loss of the cargo handled per day. Especially for cranes, their functionality is highly dependent on supply of electric power.

The correlation of damaged cranes and electric power distribution substations with the PI TCaH (Total Cargo Handled per day) is given in Figs. 41 and 42. The dependence of the port performance over the functionality of electric power substations, and thus the supply of electric power, is highly stressed.
Fig. 38. Moving average $\mu$, $\mu+\sigma$ and $\mu-\sigma$ curves for TCoH.

Fig. 39. Mean Annual Frequency of exceedance for TCoH.

Fig. 40. Functionality of cranes and waterfronts for a specific event.
Fig. 41. Level of correlation between PI=TCaH and damaged cranes.

Fig. 42. Level of correlation between PI=TCaH and non-functional distribution substations.
This study presents the seismic risk assessment of L’Aquila gas distribution network in a performance-based earthquake engineering framework. The work is divided in three parts, the first of which describes the case study while the second part summarizes the process for the seismic performance evaluation of the network. Finally the analysis of the system is described, and results in terms of connectivity-based performance indicators are presented.

Description of the case

In the L’Aquila Region (central Italy) the gas is distributed via a 621 km pipeline network, 234 km of which with gas flowing at medium pressure (2.5-3 bar), and the remaining 387 km with gas flowing at low pressure (0.025-0.035 bar). The medium-pressure distribution network is connected to the high-pressure transmission network through three M/R stations referred to as Re.Mi stations (“REgolazione e MIsura” meaning “Regulation and Measurement” in Italian) providing gas to about 42300 customers. Pipelines are either made of steel or HDPE (High Density Polyethylene) according to the pressure level. The transformation of the medium distribution pressure into the low distribution pressure is operated via 300 Reduction Groups (RGs). For the evaluation of seismic performance within this study, the medium-pressure portion of the L’Aquila gas system was selected. In particular, the selected part (shown in Fig. 43) is characterized by 3 M/R stations, 209 RGs, and pipelines at medium pressure, either made of steel or HDPE.

Risk analysis

The analysis consisted of five main steps:

- **Seismic input assessment** considering as source the Paganica fault on which L’Aquila 2009 earthquake was originated. The strong ground motion in terms of peak ground acceleration (PGA) was evaluated through the Akkar and Bommer (2010) ground motion prediction equation (GMPE) and the spatial variability was modelled using correlation
models provided by Esposito and Iervolino (2011). Values were computed before on a regular grid covering the gas network and then at each site of the network interpolating the grid values. Then peak ground velocity (PGV) was determined for each site through conditional distributions (Iervolino et al., 2010). Finally each site of the network was characterized according to the site classification scheme adopted by the GMPE.

- **Evaluation of the permanent ground deformation (PGD) hazard**: the landslide potential of L’Aquila region, according to the HAZUS (FEMA, 2004) procedure was performed. Therefore, a critical acceleration map of L’Aquila region, based on the lithological group, slope angle, and ground-water condition was obtained.

- **Seismic demand evaluation** for each component of the network. For buried pipelines ALA (2001) Poisson repair rate function of PGV and PGD were selected for each pipe typology and diameter, according to analysis of damage occurred on the gas network following the 6th April 2009 L’Aquila earthquake (Esposito, 2011). Regulator stations were not considered seismically vulnerable. For the M/R station, instead, a lognormal fragility curve for un-anchored compressor stations (FEMA, 2004) was adopted.

Fig. 43. Case study network portion

- **Seismic demand evaluation** for each component within the network. For buried pipelines ALA (2001) Poisson repair rate (RR) function of PGV and PGD were selected for each pipe typology (steel and HDPE) and diameter, according to analysis of damage occurred on the gas network following the 6th April 2009 L’Aquila earthquake (Esposito, 2011).
Regulator stations were not considered seismically vulnerable. For the M/R station, instead, a lognormal fragility curve for un-anchored compressor stations (FEMA, 2004) was adopted.

- **Systemic performance analysis** via a connectivity algorithm to integrate the damage of stations and distributing elements to evaluate the damage to the system. In particular, the system is considered functional if demand nodes (regulator groups) continue to provide gas and if they remain accessible from at least one supply node (M/R station).

- **Probabilistic risk assessment** of the case study network in terms of probability of exceeding a predefined level \( u \) of two performance indicators, PIs (i.e. Serviceability Ratio/SR and Connectivity Loss/CL), given the occurrence of an earthquake on the fault, using Monte Carlo simulation.

**Results**

Fig. 44 shows the probability of exceedance (complementary cumulative distribution function, ccdf) of the two PIs computed considering different regular grids (i.e. 1 km, 2km, 5 km) in order to study the effects of regular grid size for the computation of intensity measures. Then a performance disaggregation analysis was performed in order to identify the values of some variables providing the largest causative contribution to the risk given exceedance or occurrence of specified values of the performance indicator. Conditional distributions were performed for the number of broken pipes, damaged M/R stations and the percentage of pipes vulnerable to PGD. As illustrative example Fig. 45 shows the distribution of the number of damaged M/R stations conditional to the occurrence of the two PIs to ten intervals (equally spaced and ranging from 0 to 1); see Esposito and Iervolino (2013) for details.
Fig. 44. Ccdf for CL (left) and SR (right)

Fig. 45. Relative frequency of the number of damaged M/R stations conditional to CL (left) and SR (right)
The road network of Calabria region, in Southern Italy, has been chosen as the case study. The region has not been affected by significant earthquakes in recent times, hence the study is more a real scale application to test the capabilities of the SYNER-G methodology and software rather than a validation study.

The network is composed of 2861 nodes and 5970 edges (Fig. 46a). The nodes are subdivided into Traffic Analysis Zone (TAZ) centroids and simple intersections. The former, representing municipalities, are the origin-destination (OD) nodes, while the latter serve the purpose of describing the network topology and are located where two or more edges converge. Edges, that are the only vulnerable components in the network, are subdivided into road segments and bridges, with fragility models expressed in terms of peak ground displacement (PGD) and peak ground acceleration (PGA), respectively. Edges are also classified as either main roads (principal roads or highway) or secondary roads, based on their free flow speed. Within the developed model the RDN is modelled as a directed graph and all edges have a travelling direction, from node i to node j; for this network, all edges are two-ways roads, effectively making the graph undirected. Finally, the graph is a weighted one, with weights being the free flow travel times of edges.

The seismic hazard is modelled through 20 faults taken from the Italian DISS (Database of Individual Seismogenic Sources) database, employing the truncated Gutenberg&Richter recurrence model for the source activity (Fig. 464b).

Further available data include the location of the ten public hospitals, belonging to the regional health-care system, and of the landsliding susceptible areas, as well as detailed fragility data for 11 important bridges.
With reference to an undamaged network, i.e. non-seismic conditions, different models exist in the literature for the estimation of trip generation and trip distribution over a network. In such conditions, the computation of the origin-destination matrix, the link flows and congested travel times is straightforward. On the other hand, the literature lacks of traffic demand models for a seismically damaged network. In this case, the number of attracted and generated trips for each TAZ should ideally be estimated according to people accessibility to the RDN and their needs in the emergency post-earthquake phase; consequently, the travel demand is likely to be completely different from that in the normal operating conditions. For this reason, it has been decided to analyse network performance in terms of pure connectivity.

Three types of simulation have been carried out: plain Monte Carlo (MCS) and Importance Sampling with and without k-means clustering. Such methods have been compared with reference to some selected performance indicators (PI’s):
- **Minimum travel time** needed to reach one of the hospitals, computed for each TAZ centroid;

- **Simple Connectivity Loss (SCL)**, that measures the average reduction in the ability of sinks to receive flow from sources: $SCL = 1 - \left\langle \frac{N_s^i}{N_0^i} \right\rangle$, where $\langle \rangle$ denotes averaging over all sink vertices, while $N_s^i$ and $N_0^i$ are the number of sources connected to the $i$-th sink in the seismically damaged network and in non-seismic conditions, respectively. All the single TAZ’s, taken one at a time, are considered sinks, whereas all the remaining TAZ’s are sources;

- **Weighted Connectivity Loss (WCL)**, that upgrades the simple connectivity loss by weighting the number of sources connected to the $i$-th sink, in seismic and non-seismic conditions, respectively: $WCL = 1 - \left\langle \frac{N_s^i \cdot W_s^i}{N_0^i \cdot W_0^i} \right\rangle$, where the weights $W_s^i$ and $W_0^i$ can be defined in different ways. Herein they are defined as the sum of the inverse of travel times of the single paths between the $i$-th sink and the sources, in the seismically damaged network and in non-seismic conditions, respectively;

- **Moving average $\mu$ and moving standard deviation $\sigma$ of SCL and WCL**;

- **Terminal Reliability (TR)**, indicating the probability that a path exists between a specific OD pair;

- **Mean Annual Frequency (MAF) of exceedance of SCL and WCL**.

The main analysis results are presented in the following figures, as obtained from the plain MCS (20000 runs, shown to yield stable estimates for all considered PI’s).

Fig. 47 shows the moving average $\mu$ curves for SCL (a) and WCL (b), as well as the $\mu+\sigma$ and $\mu-\sigma$ curves for the two PI’s. 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 TAZ’s, but also the increase in travel time due the seismically induced damage suffered by the RDN.
Fig. 47. Moving average $\mu$ curves for (a) SCL and (b) WCL

Fig. 48a shows the MAF of exceedance curves for SCL and WCL (left). As expected, weighting the computation of connectivity loss with the path travel times yields higher values of exceedance frequency. Fig. 48b displays, in a matrix form with a grey scale, the values of TR for each pair of TAZ’s.

The matrix, which is symmetric since the graph is undirected, indicates that the probability of connection is very high over the entire region, with lower reliability concentrated in the northern part of Calabria (approximately the first 100 TAZ’s).

Fig. 49 shows two contour maps of travel time to the closest hospital (a) and of its increment in damaged conditions (b), respectively. The blue “islands” (Fig. 49a), with zero travel time, clearly indicate the hospitals’ positions in the region. The travel time increment results to be very low and concentrated in the central mountainous part of the region.
Fig. 48. MAF curves for (a) SCL and WCL and (b) TR matrix

Fig. 49. Contour maps for (a) minimum travel time and (b) travel time increment
The power network of Sicily, one of the Italian major islands, has been chosen as the case study. As for the RDN case, the island has not been affected by significant earthquakes in recent times, hence the study is more a real scale application to test the capabilities of the SYNER-G methodology and software rather than a validation study.

The network is composed of 181 nodes and 220 transmission lines (Fig. 50). The nodes, i.e. the buses, are subdivided into 175 demand or load nodes and 6 supply nodes, 5 of which are power plants and 1 is the balance node (or slack bus). The load nodes (two for transmission/distribution and one for distribution substations) deliver power to users. The total number of municipalities served by the network is 390. The balance node, generally coinciding with the generation node providing the highest power, is introduced in the adopted power flow formulation (see later) since power losses in the network are unknown before solving the power flow equations. Its function is to provide the power balance between the power ingoing at generation nodes and the power outgoing from load buses, plus the power losses. All transmission lines are overhead lines and not considered as vulnerable elements. They are classified into high (HV), medium (MV) and low voltage (LV) lines. The EPN is modelled as an undirected un-weighted graph.

The seismic hazard is modelled through 18 faults taken from the Italian DISS (Database of Individual Seismogenic Sources) database, employing the truncated Gutenberg & Richter recurrence model for the source activity.
Fig. 50. Electric power network of Sicily and municipalities' position
The analysis of an EPN in a seismically active environment can be carried out at two different levels. The first basic one, which focuses on connectivity only, is particularly inadequate for a system such as the EPN since the tolerance on the amount and quality, in terms of voltage and frequency, of the power fed to any demand node for maintaining serviceability is very low. The actual power flow in the node must be determined to make any meaningful statement on the satisfaction of the power demand at the node, not just its state of continued connectivity. The latter is an intrinsically systemic problem since it depends on the determination of the flows on the entire (damaged) network. Further, before being able to evaluate flows it is necessary to determine what is the EPN portion still up and running after an event. Indeed, damage to the components of a substation can lead to a short-circuit that may or may not propagate further away from that substation to adjacent others, generating in extreme cases very large black-outs. Hence, in this modelling approach, power flow analysis follows the analysis of short-circuit propagation, in which circuit breakers are active components playing a key role in arresting the short-circuit spreading. Moreover, the substations are not modelled as vulnerable points, characterised by an assigned fragility function: their full internal logic is modelled, to account for partial functioning (continued service with reduced power flow). The eleven typologies of micro-components composing the load substations are the only elements in the network that are considered vulnerable. For such elements, fragility curves function of peak ground acceleration (PGA) are available.

Three types of simulation have been carried out: plain Monte Carlo (MCS) and Importance Sampling with and without k-means clustering. Such methods have been compared with reference to some selected performance indicators (PI’s):

- **Connectivity Loss (CL)**, that measures the average reduction in the ability of sinks to receive flow from sources: $CL = 1 - \langle N_s^i / N_0^i \rangle_i$, where $\langle \rangle$ denotes averaging over all sink vertices, while $N_s^i$ and $N_0^i$ are the number of sources connected to the $i$-th sink in the seismically damaged network and in non-seismic conditions, respectively. Sinks are load buses and sources are power plants;

- **Power Loss (PL)**, that upgrades the connectivity loss with the size of the power plants (in MW) to which sink vertices are still connected to: $PL = 1 - \langle P_s^i / P_0^i \rangle_i$, where $P_s^i$ and $P_0^i$ are the sum of the real power of all the power plants connected to the $i$-th load bus in the seismically damaged network and in non-seismic conditions, respectively. PL can be seen as a weighted CL. For the case study in exam, PL yields the same values as CL, since all power plants generate the same power.
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- **System Serviceability Index (SSI)**, that is defined as the ratio of the sum of the real power delivered from load buses after an earthquake, to that before the earthquake:

\[
SSI = \frac{\sum_{i=1}^{N_0} P_{i,0} \cdot (1 - R_i) \cdot w_i}{\sum_{i=1}^{N_0} P_{i,0}} \cdot 100
\]

where \( P_{i,0} \) is the real power delivered from the \( i \)-th load bus in non-seismic conditions, i.e. the demand. \( R_i = \frac{|V_{i,s} - V_{i,0}|}{V_{i,0}} \), with \( V_{i,s} \) and \( V_{i,0} \) the voltage magnitudes in seismic and non-seismic conditions, is the percent reduction of voltage in the \( i \)-th load bus. The factor \( w_i \) is a weight function accounting for the small tolerance on voltage reduction: its value is 1 for \( R_i \leq 10\% \) and 0 otherwise. The SSI index ranges between 0 and 100, assuming the value 0 when there is no solution for the power-flow analysis and 1 when the EPN remains undamaged;

- **Voltage Ratio (VR)**, defined for each load bus as the ratio of the voltage magnitude in the seismically damaged network to the reference value for non-seismic, normal conditions:

\[
VR_i = \frac{V_{i,s}}{V_{i,0}}
\]

- **Moving average \( \mu \) and moving standard deviation \( \sigma \) of CL, PL and SSI**;

- **Mean Annual Frequency (MAF) of exceedance of CL, PL and SSI**.

The main analysis results are presented in the following figures, as obtained from the plain MCS (20000 runs, shown to yield stable estimates for all considered PI’s). Fig. 51 shows the moving average \( \mu \) curves for CL (a) and SSI (b), as well as the \( \mu + \sigma \) and \( \mu - \sigma \) curves for the two PI’s. The minimum sample size is strongly dependent on the chosen PI (SSI stabilises with less than 1000 runs). The reason for CL requiring a much larger number of runs 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. 51. Moving average μ curves for (a) CL and (b) SSI

Fig. 52. MAF curves for (a) CL and (b) SSI
Fig. 52 shows the MAF of exceedance curves for CL and SSI. The same feature highlighted by the moving average of the two PI’s 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. 53 shows a contour map, reporting 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.
As far as health-care facilities are concerned, the application carried out has focused on two aspects: the probabilistic assessment/characterization of a single facility according to the developed methodology, and the assessment of the capacity of a regional system of health-care facilities to collectively cope with the treatment demand following a disaster.

The chosen health-care facility is the Lamezia Terme public hospital, an old RC structure comprising two main, quite different buildings (denoted as Piastra and Degenze in Fig. 54), dating from the ‘70s and located in the Calabria region already shown with reference to the RDN analysis. According to the developed methodology and established practice in the modelling of complex-social systems, the hospital has been modelled in terms of its three macro-components: physical, human and organizational. The single facility performance as been expressed through the Performance Indicator:

- Hospital Treatment Capacity (HTC$_1$) defined as the product of three factors reflecting the above mentioned macro-components: HTC$_1$ = $\alpha\beta\gamma/t_m$. HTC$_1$ represents the number of seriously injured casualties (a fraction of the total, evaluated based on physical damage to the building stock in the affected region, district by district, and allocated to hospitals with an iterative algorithm) that can be given surgical treatment in an hour. $t_m$ is the average duration in hours of a single treatment, while $\gamma$ is the number of functional and staffed operating theatres, given optimal organizational and human (training) factors ($\alpha=\beta=1$).
A second PI employed to characterize the facility performance (HTC₂) is the number of beds available for hospitalization, which must exceed the total number of casualties arriving at the hospital and requiring any kind of treatment (surgical and not surgical), for satisfactory performance.

Fig. 54. The Lamezia Terme public hospital

A second PI employed to characterize the facility performance (HTC₂) is the number of beds available for hospitalization, which must exceed the total number of casualties arriving at the hospital and requiring any kind of treatment (surgical and not surgical), for satisfactory performance.

Fig. 55. The essential medical services and basic services
The evaluation of the factor $\gamma$ is the core of the assessment methodology for a single facility and employs a fault-tree analysis to identify availability in the damaged facility of a previously identified set of essential medical services. This is a sub-set (highlighted on the left part of Fig. 55) of all medical services that is needed in order for surgical treatment to be administered to the severely injured. Performance requirements for the structures housing the services are correspondingly different: operational for the essential services and just structural integrity for other (basic) service.

Fig. 56 shows the fault tree of the physical component of the hospital facility (basically the collection of structural and non-structural elements making up the facility) for both basic and essential medical services.

Fig. 56. Fault tree of the physical components of the hospital

Evaluation of this FT for the damaged state of the facility allows determination of the Boolean component $\gamma_1$ of $\gamma=\gamma_1\gamma_2$, which takes upon the value of 1 when the services are available. The other factor equals the maximum number of operating theatres in emergency conditions (according to the
emergency plan, and including normally operated theatres and additional emergency ones) minus those directly damaged from the earthquake. This number equals at most 8 in the case of the Lamezia Terme hospital.

Characterization of the single facility for use in systemic analysis proceeds with determination of the probability distribution of HTC₁ and HTC₂, conditional on the chosen seismic intensity measure. This is done through a two-step simulation:

- A preliminary small-sample simulation is employed to collect structural responses through inelastic response history analysis of structural models of the facility buildings (two in this case) under a suite of (a few tens of) ground motion time-series. Structural responses of interest are those needed to evaluate structural performance/failure (shear as well as flexural deformation in columns and beams, stresses in joints), but also the performance level of non-structural elements (hence floor accelerations and inter-storey drifts).

- A Monte Carlo simulation during which structural responses and structural and non-structural capacities are repeatedly sampled, the former from a joint model set up based on the results of the preliminary simulation, the latter from capacity models incorporating epistemic/model as well as aleatoric uncertainty.

The final result is shown in Fig. 43, in the form of the second moment characterization of the daily number of surgical treatments as a function of PGA. The number is arrived at by multiplying the HTC₁ value (with $\alpha = 1$, $\beta = 0.8$ and $t_m = 2$ hours) times 24 hours/day.
The prototype software in the SYNER-G project is based on the EQvis-platform. This platform is written in Java in the development environment Eclipse. Embedded in the platform there are various plug-ins. One plug-in is the OOFMIS software. In general the platform comprises a consequent based risk management tool for seismic events. Another plug-in would be the Fragility Manager Tool, which has also been created in the project. All these individual software tools were integrated in one software package (EQvis).

Fig. 58. The Software Tool of SYNER-G
The platform is not only for researchers and developers, but to help decision makers make decisions. It serves as a decision support tool, which should be easy to handle.

The field of analyses that can be performed with EQvis is very large, e.g. Hazard Computation, Structural Damages, Functionalities, Repair Cost Estimations, Cost Benefit Analyses, Utility Network Damages, Multi Attribute Utility Analyses, Shelter Needs, Social Vulnerability, Temporary Housing, etc.
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Fig. 60. Demonstration Case - The City of Vienna

The Fragility Manager Tool offers the user to combine certain fragility functions and store them directly on the platform and use them. With the Fragility Manager, the test case in the city of Vienna has been tested successfully. The platform can take the fragility curves for all buildings and bridges and assign them to all the objects correctly. In the next step different analyses can be computed.

Work Package 4 delivered another plug-in: The socio-economic module. The connection between the OOFIMS module and the socio-economic module was computed and the output was again realised through GIS data format.
The modularity of EQvis is the key for such a successful software tool. Due to its plug-in based nature the tool can be improved very quickly. In SYNER-G the software tools of the various work packages have been implemented successfully. The linkage between the tools was created via EQvis and the visualisation part was programmed in a GIS format.

SYNER-G helped creating a very effective future-oriented tool with a sound scientific basis.
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