Systemic Seismic Vulnerability and Risk Analysis of Urban Systems, Lifelines and Infrastructures

Kyriazis Pitilakis[1], Sotiris Argyroudis[2]

[1] Department of Civil Engineering, Aristotle University of Thessaloniki
P.O.B. 424, 54124, Thessaloniki, Greece
kpitilak@civil.auth.gr

[2] Department of Civil Engineering, Aristotle University of Thessaloniki
P.O.B. 424, 54124, Thessaloniki, Greece
sarg@civil.auth.gr

ABSTRACT:

The basic concepts and some representative results of the work carried out within the European collaborative research project SYNER-G (http://www.syner-g.eu) are presented in this paper. The overall goal is to develop an integrated methodology for systemic seismic vulnerability and risk analysis of urban systems, transportation and utility networks and critical facilities. SYNER-G developed an innovative methodological framework for the assessment of physical as well as socio-economic seismic vulnerability and loss assessment at urban and regional level. The built environment is modeled according to a detailed taxonomy into its components and sub-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 way all aspects in the chain, from regional hazard to vulnerability assessment of components to the socioeconomic impacts of an earthquake, accounting for relevant uncertainties within an efficient quantitative simulation scheme, and modeling interactions between the multiple component systems in the taxonomy. The prototype software (OOFIMS) together with several complementary tools are implemented in the SYNER-G platform, which provides several pre and post-processing capabilities. The methodology and software tools are applied and validated in selected sites and systems in urban and regional scale. Representative results of the application in the city of Thessaloniki are presented here.

Keywords: systemic analysis, earthquakes, vulnerability, risk, socioeconomic loss, buildings, lifelines, infrastructures, interactions

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1 Introduction

So far seismic vulnerability and risk assessment are performed at system level. i.e. bridge, building, water network etc. The losses are estimated at “element at risk” or at the best at system level. Then they are somehow integrated at urban or regional level to account in an elementary way the socio-economic impact. However, in reality the different systems composing an urban or industrial system are strongly interconnected to each other. For example the transportation system with the medical care system or the production and supply chain; the electrical power with almost all other systems. The real losses, physical, economic and human, are normally higher or much higher when we account the interaction among systems.

The aim of SYNER-G [1] is to tackle this issue and develop for a first time in Europe and in certain degree worldwide, a methodology to analyse systems in case of earthquakes considering inter and intra-dependencies. The goal is to establish an integrated methodology for systemic seismic vulnerability and risk analysis of buildings, different lifelines (transportation and utility networks) and critical facilities. The methodology, which is implemented in an open source software tool, integrates within the same framework the hazard, the physical vulnerability and the social consequences/impact at a system level. It is applied and validated in selected case studies at urban and regional scale: the city of Thessaloniki (Greece), the city of Vienna (Austria), the harbor of Thessaloniki, the gas system of L’Aquila (Italy), the main electric power network in Sicily, a roadway network in South Italy and a hospital facility again in Italy. In the present paper we present only some examples from the application in Thessaloniki.

Systemic studies commonly address the following two phases: a) *emergency*: short-term (a few days/weeks) at the urban/regional scale, b) *economic recovery*: medium to long-term, at the regional/national scale. SYNER-G focuses mainly on the first phase with emergency managers and insurances being the main reference stakeholders. The goal is to forecast before the strong earthquake event the expected impact for the purpose of planning and implementing risk mitigation measures. We present herein the basic concepts of the methodology and several representative results.

2 SYNER-G methodology

The goal of the SYNER-G general methodology is to assess the seismic vulnerability of an infrastructure of urban/regional scale, accounting for inter- and intra-dependencies among infrastructural components, as well as for the uncertainties characterizing the problem. The goal has been achieved setting up a model of the infrastructure and of the hazard acting upon it, and then enhancing it with the introduction of the uncertainty and of the analysis methods that can evaluate the system performance accounting for such uncertainty.

The infrastructure model actually consists of two sets of models: the first set consists of the physical models of the systems making up the infrastructure. These models take as an input the hazards and provide as an output the state of physical/functional damage of the infrastructure. The second set of models consists of the socio-economic models that take among their input the output of the physical models and provide the socio-economic consequences of the event. The SYNER-G methodology integrates these models in a unified analysis procedure. In its final form the entire procedure is based on a sequence of three models: a) seismic hazard model, b) components' physical vulnerability model, and c) system (functional and socio-economic) model.

For illustration purposes, with reference to the two socio-economic models identified and studied within SYNER-G (the SHELTER and HEALTH-CARE models), Figure 1 shows in qualitative terms the integrated procedure that leads from the evaluation of the hazard to that of the demands on the shelter and health-care system in terms of Displaced Population and Casualties, down to the assessment of social indexes like the Health Impact and the Shelter Needs. For more details the reader is referred to SYNER-G Reference Reports 1 [2] and 5 [3].

The conceptual sketch in Figure 1 can be practically implemented by developing:

- A model for the spatially distributed seismic hazard.
- A physical model of the infrastructure.
- Socio-economic models.

Development of the hazard model has the goal of providing a tool for: a) sampling events in terms of location (epicenter), magnitude and faulting type, according to the seismicity of the study region; b) predicting maps of seismic intensities at the sites of the vulnerable components in the infrastructure. These maps, conventionally conditional on M and epicenter, should correctly describe the variability and spatial correlation of intensities at different sites. This is important because systems are extended in space. Further, when more vulnerable components exist at the same location and are sensitive to different intensities (e.g. acceleration, velocity, strains and displacement), the model should predict intensities measures (IM) that are consistent at the same site.

Development of the physical model starts from the SYNER-G Taxonomy and requires: a) for each system within the Taxonomy, a description of the functioning of the system under both undisturbed and disturbed conditions (i.e. in the damaged state following an earthquake); b) a model for the physical and functional (seismic) damageability of each component within each system; c) identification of all dependencies between the systems; d) definition of adequate performance indicators (PI) for components and systems, and the infrastructure as a whole.

Development of the socio-economic model starts with an interface to outputs from the physical model in each of the four domains of SYNER-G (i.e., buildings, transportation systems, utility systems and critical facilities). Thus, four main performance indicators - Building Usability, Transportation Accessibility, Utility Functionality and Healthcare Treatment Capacity - are used to determine both direct and indirect impacts on society. A similar layout could be established at an industrial complex level. Direct social losses are computed in terms of casualties and displaced populations. Indirect social losses are considered, for the moment, in two models - Shelter Needs and Health Impact - which employ the multi-criteria decision analysis (MCDA) theory for combining performance indicators from the physical and social vulnerability models.

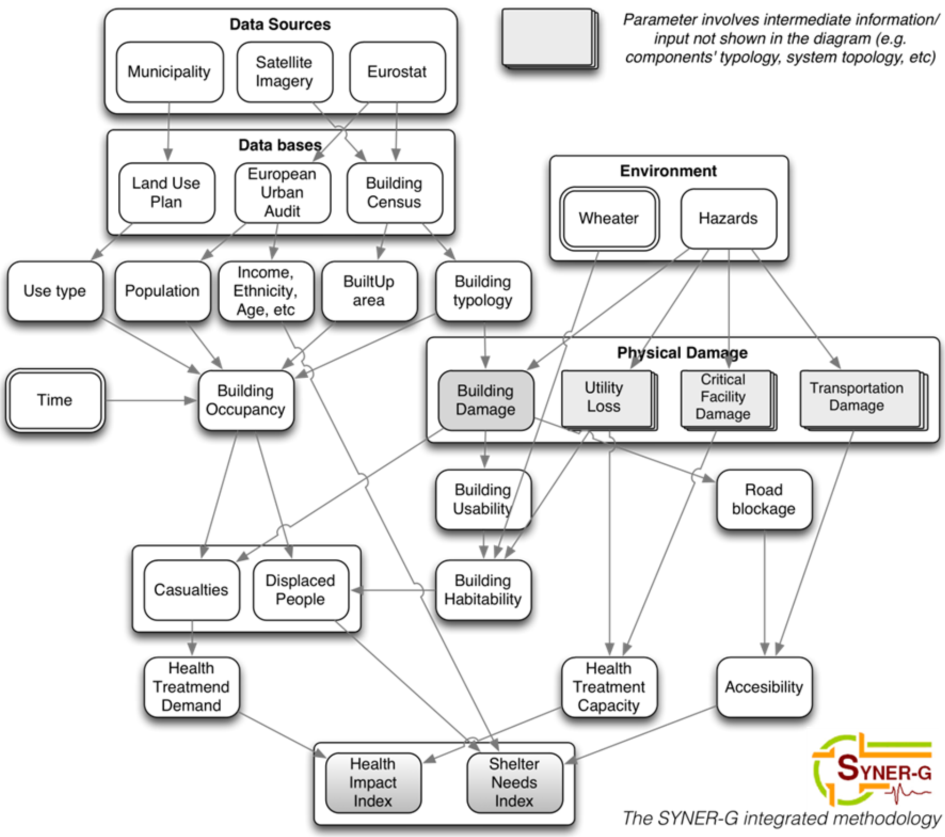

Figure 1: Integrated evaluation of physical and socio-economic performance indicators [2]

In order to tackle the complexity of the described problem the object-oriented paradigm (OOP) has been adopted. In abstract terms, within such a paradigm, the problem is described as a set of objects, characterized in terms of attributes and methods, interacting with each other [2]. Objects are instances (concrete realizations) of classes (abstract models, or templates for all objects with the same set of properties and methods). Figure 1 provides a general view of the methodological diagram.

3 SYNER-G Taxonomy

It is an essential step in urban earthquake risk assessment to compile inventory databases of elements at risk and to make a classification on the basis of pre-defined typology/taxonomy definitions. Typology definitions and the classification system should reflect the vulnerability characteristics of the systems at risk, e.g. buildings, lifeline networks, transportation infrastructures, etc., as well as of their elements at risk and sub-components in order to ensure a uniform interpretation of data and risk analyses results. Within SYNER-G a detailed taxonomy of a set of systems, sub-systems and components (elements) was identified and described, in an homogeneous way, based on all available databases and national practices in Europe and if necessary at international level. This taxonomy has been the guidance for the proposed fragility models and the modelling of systems in the next steps. The SYNER-G taxonomy is the first homogeneous ontology and taxonomy in Europe for all systems exposed at seismic risk. For more details the reader is referred to SYNER-G Reference Report 2 [4].

4 Seismic Hazard

The definition of seismic scenarios requires the development of a precise methodology for characterising the hazard input in a manner that is appropriate for application to the analysis of multiple and spatially distributed infrastructures. For novel applications such as the present one, conventional approaches for the estimation of seismic hazard are insufficient to characterise the properties of ground motion, and spatial variability, that are most relevant for each infrastructure. In accordance to the fragility models, an extensive literature review was undertaken to identify initially the best means of determining the most appropriate intensity measures (IM) for a given element, and then identifying the most efficient intensity measure for each element or collection of elements within an infrastructure [5].

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, called herein ***"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 (Figure 2). This is a 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 variants, representing the residual term of the ground motion prediction equation (GMPE).

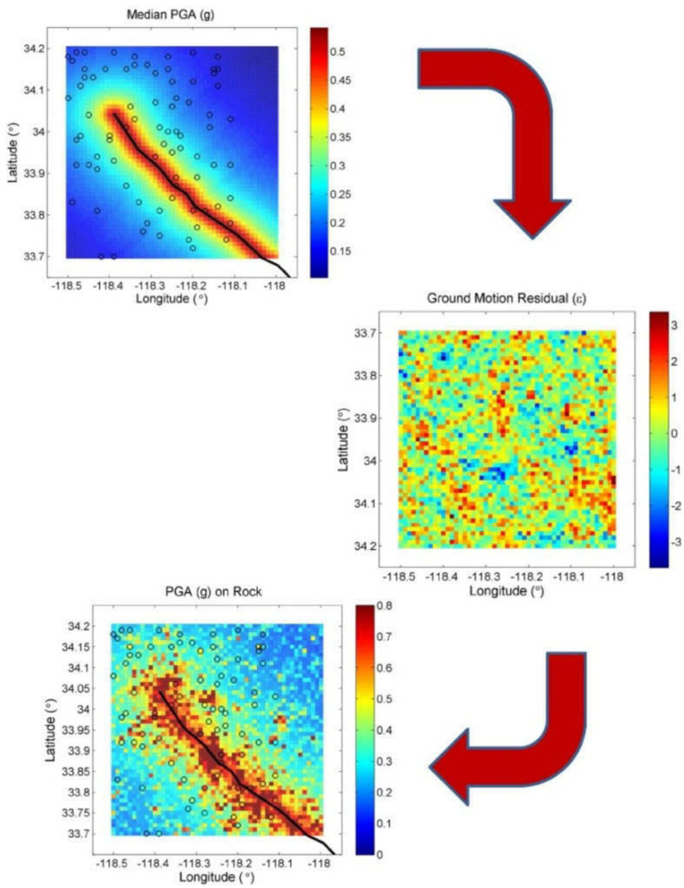

Figure 2: Overview of the "Shakefield" methodology, including the attenuation of ground motion from an event and the generation of correlated Gaussian fields as a means of simulating spatial correlation and cross-correlation in the GMPE residual term [2]

For utility systems (water and gas pipeline systems) as well as for similar systems with linear elements, fragility models are generally given in terms of permanent ground displacement (PGD), as they are most vulnerable to the permanent displacement of the ground (i.e. liquefaction or landsliding induced displacements) rather than transient shaking. To this extent "Shakefield" was further extended to incorporate geotechnical type hazards, including of course site amplification, but also liquefaction, co-seismic slope displacement and transient strain. This extension is inspired from HAZUS [6] software, with its corresponding probability definitions now interpreted in a stochastic context. However, several elements of the HAZUS model that relate the expected PGD to the strong seismic 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, while new site amplification factors will be implemented in the near future [7, 8].

5 Fragility Curves

Fragility curves constitute one of the key elements of seismic risk assessment. They relate the seismic intensity to the probability of reaching or exceeding a level of damage (e.g. minor, moderate, extensive, collapse) for each element at risk. For buildings and bridges the level of shaking can be quantified using different earthquake intensity parameters, including peak ground acceleration/velocity/displacement, spectral acceleration, spectral velocity or spectral displacement. For other elements at risk other forms and IMs are used (i.e. repair ratio per km for pipelines correlated to PGV or PGD). They are often described by a lognormal probability distribution function, although it is noted that this distribution may not always be the best fit. Several approaches can be used to establish the fragility curves that can be grouped under empirical, judgmental, analytical and hybrid. The key assumption in the vulnerability assessment of buildings and lifeline components is that structures having similar structural characteristics, and being in similar geotechnical conditions, are expected to perform in the same way for a given seismic loading. Within this context, damage is directly related to the structural properties of the elements at risk. Typology is thus a fundamental descriptor of a system, derived from the inventory of each element.

One of the main contributions of SYNER-G is the compilation of the existing fragility curves/functions and development of new functions for all the system elements based on the proposed taxonomy. A literature review on the typology, fragility functions, damage scales, intensity measures and performance indicators has been performed for all the elements. The fragility functions are based on new analyses and collection/review of the results that are available in the literature. In some cases, the selection of the fragility functions has been based on validation studies using damage data from past and recent earthquakes mainly in Europe. Moreover, the damage and serviceability states have been defined accordingly. Appropriate adaptations and modifications have been made to the selected fragility functions in order to satisfy the distinctive features of the presented taxonomy. In other cases, new fragility functions have been developed based on numerical analyses (i.e. tunnels, road embankments/cuts, bridge abutments) or by using fault tree analysis together with the respective damage scales and serviceability rates in the framework of European typology and hazard [9].

A "***Fragility Function Manager Tool***" has been 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. For each fragility function set, the metadata of the functions, representative plots and the parameters of the functions can be visualized in an appropriate panel or window. Once the fragility functions are uploaded, the tool can be used to harmonise and compare the curves. The harmonisation module allows one to harmonise the curves using a target intensity measure type and a number of limit states of reference. After the harmonisation, the comparison module can be used to plot together and to compare different functions, which can then be extracted and the mean and dispersion of the parameters of the curves can be calculated. The reader may consult for more information the SYNER-G Reference Report 4 [9].

6 Socio-Economic Impact Models

The current state-of-the-art in earthquake engineering produces reasonably accurate estimates of physical damage to single elements at risk like buildings and infrastructure systems, as well as reasonable estimates of the repair and replacement costs associated with this type of damage. However, poor linkages between damage to physical systems and resultant social and economic consequences remain a significant limitation in existing loss estimation models.

A unified approach for modelling shelter needs and health impacts caused by earthquake damage, which integrates social vulnerability into the physical systems modelling approaches has been developed in SYNER-G. These two kinds of impacts have been selected as being among the most important in crisis period for the society. Figure 3 illustrates the integrated procedure that leads from the hazard to the evaluation of the demands on the shelter and health-care system, leading to the computation of two key parameters: Displaced Population (DP) and Casualties. The shelter needs and health impact models brings together the state-of-the-art social loss estimation models into a comprehensive modelling approach based on multi-criteria decision support, which provides decision makers with a dynamic platform to capture post-disaster emergency shelter demand and health impact decisions.

The focus in the ***shelter needs model*** is to obtain shelter demand as a consequence of building usability, building habitability and social vulnerability of the affected population rather than building damage alone. The shelter model simulates households' decision-making and considers physical, socio-economic, climatic, spatial and temporal factors in addition to modelled building damage states (Figure 4). The ***health impact model*** combines a new semi-empirical methodology for casualty estimation with models of health impact vulnerability, transportation accessibility and healthcare capacity to obtain a holistic assessment of health impacts in the emergency period after earthquakes. A group of socio-economic indicators were derived based on an in-depth study of disaster literature for each of the shelter, health and transport accessibility models, and harmonized based on data available for Europe from the EUROSTAT Urban Audit Database. For more details the reader may consult the SYNER-G Reference Report 5 [3].

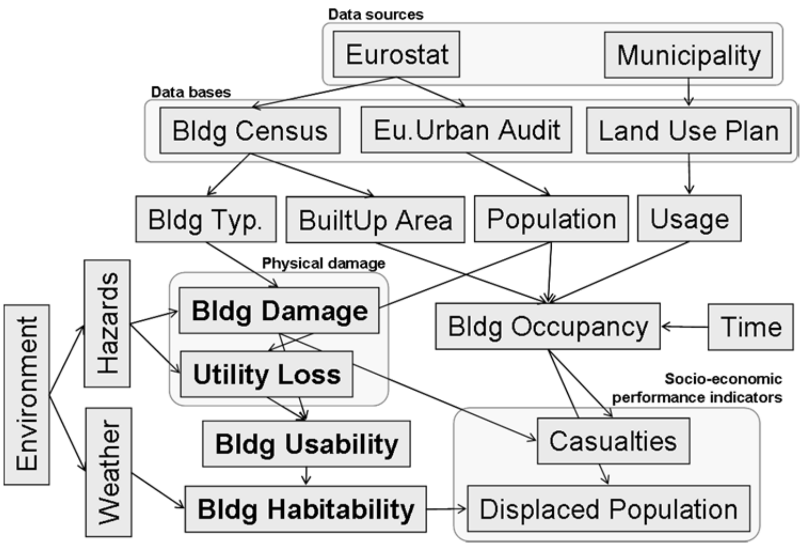

Figure 3: Integrated evaluation of physical and socio-economic performance indicators [3]

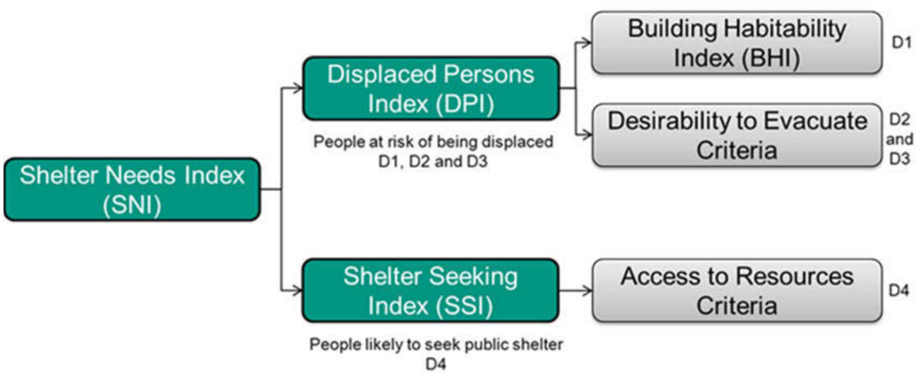

Figure 4: Multi-criteria decision model for computing Shelter Needs Index [3]

7 Systemic Analysis

Based on the SYNER-G methodology, each of the four systems considered (buildings and aggregates, utility networks, transportation networks and critical facilities) has been specified according to the following three main features [10]:

7.1 Taxonomy of components within each system

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 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.

7.2 System evaluation and performance indicators

Three main types of solving algorithms are considered in the SYNER-G approach:

- *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 are disconnected from the rest of the system. This approach is used for all utility networks (water, electricity, gas) and the road transportation system.
- *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).
- *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.

The evaluation of ***Performance Indicators*** at the component or the system level depends 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).

7.3 Interdependencies

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

- *"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.
- *Physical interactions:* they are associated with exchanges of services or supplies between systems, like the supply of 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.
- *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.

8 SYNER-G Software Tools

A comprehensive tool box has been developed **(EQvis)** containing several pre and post-processing tools as well as other plug-ins such as the prototype software (OOFIMS), the Fragility Manager Tool, the MCDA software for modelling shelter needs and health impact (Figure 5). The product EQvis (European Earthquake Risk Assessment and Visualisation Software) is an open source product that allows owners, practicing engineers and researchers the realistic risk assessment on systemic level (Figure 6). It has been based on the similar pre and post-processing modules of MAEviz [11].

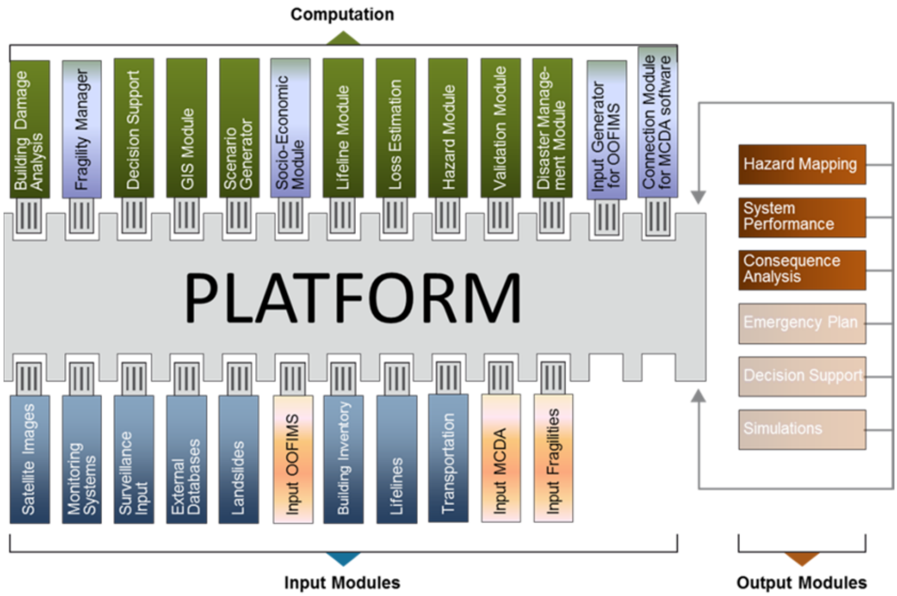

Figure 5: The plug-in based structure of the software

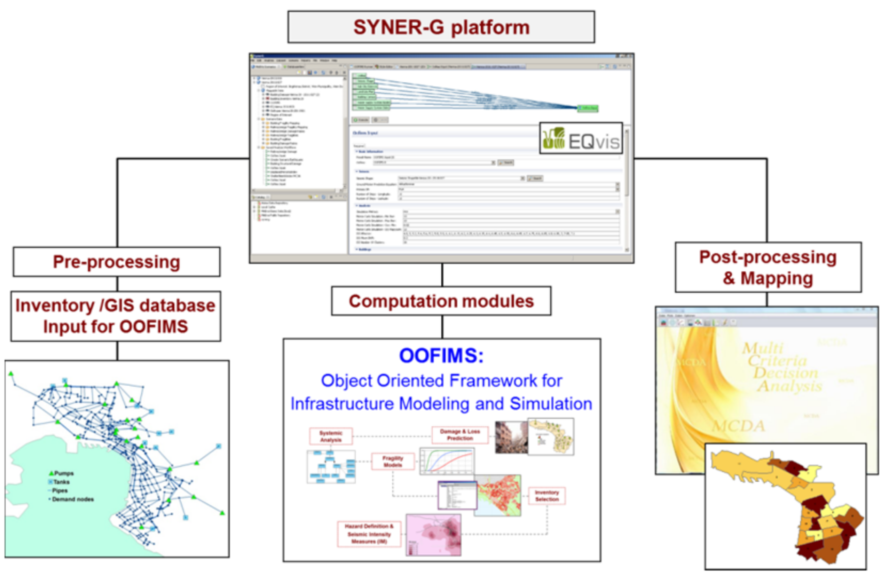

Figure 6: Layout of the SYNER-G platform

9 Application to Thessaloniki

To demonstrate the SYNER-G methodology and its tools we present in the following some representative results for the application in Thessaloniki, Greece, which is located in a high seismicity area and disposes a very good data base of all element at risk and geotechnical conditions. The study area covers the municipality of Thessaloniki, which is divided in 20 Sub City Districts as defined by Eurostat and Urban Audit approach. The case study presented herein includes the following elements: building stock (BDG), road network (RDN), water supply system (WSS) and electric power network (EPN). The networks comprising the main lines and components 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).

A Monte Carlo simulation (MCS) has been carried out (10,000 runs) based on the methods and tools developed in SYNER-G. Each sampled event represents a single earthquake ("Shakefields" method) and all systems are analysed for each event. The results are then aggregated all over the sampled events. In this way, all the characteristics of each event (e.g., spatial correlations) are accounted for and preserved for the systemic analysis. For each system, selected Performance Indicators (PI's) are calculated based on the estimated damages and functionality losses of the different components.

The overall performance of each network is expressed through the Mean Annual Frequency (MAF) of exceedance and the moving average μ and moving standard deviation σ of the PIs. Thematic maps showing the distribution of expected damages/ losses are produced for selected events. Moreover, the significant elements for the functionality of each system are defined through correlation factors to the system PIs. 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.

9.1 Fragility curves

New fragility curves have been developed for buildings (masonry, R/C) and bridges of Thessaloniki [9, 12]. 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. Fragility curves for RC buildings that account for shear failure and consider model uncertainties and the scatter of material and geometric properties were also produced following the assessment method of EC8. Analytical fragility curves were developed for specific bridge typologies 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., Figure 7a). On the other hand, modern bridges are less vulnerable (e.g. Figure 7b).

For other elements (road pavements, pipelines etc.), appropriate fragility functions are developed based on the fragility models and IMs suggested in SYNER-G [9].

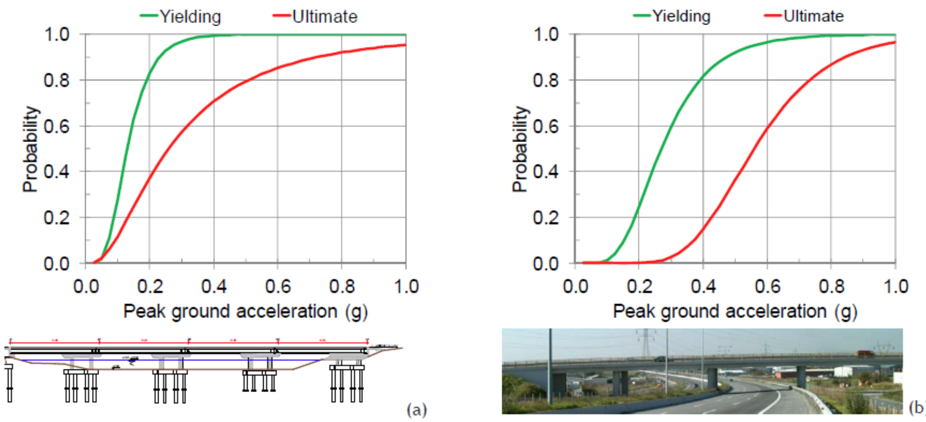

Figure 7: Example of fragility curves for Thessaloniki application (a) a bridge with the deck supported on bearings, constructed in 1985 with the old seismic code and (b) an overpass with monolithic deck-pier connection, constructed in 2003 with the new seismic code

9.2 Seismic Hazard

Five seismic zones are selected for the seismic hazard input, obtained by SHARE European research project [13]. Following the specification provided in SYNER-G the ground motion prediction equation (GMPE) introduced by Akkar and Bommer [14] is applied for the estimation of the ground motion parameters on rock basement, while the spatial variability is modelled 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, the current EC8 [15] amplification factors are used. For the liquefaction hazard the modelling approach proposed in HAZUS [6] is adopted for the estimation of PGD at the vulnerable sites. A detailed description of the entire hazard model adopted in the methodology can be found in Franchin et al. [16] and Weatherhill et al. [17].

9.3 Electric Power Network

Figure 8 shows the moving average (mean) curve for Electric power Connectivity Loss (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. The MAF of exceedance for ECL is also shown in Figure 8. The ECL with mean return period Tm=500 years (λ=0.002) is 24%. Functional and non-functional components (transmission substations and demand nodes-WSS pumping stations) for a seismic event (#6415) corresponding to the specific return period of ECL are shown in Figure 9.

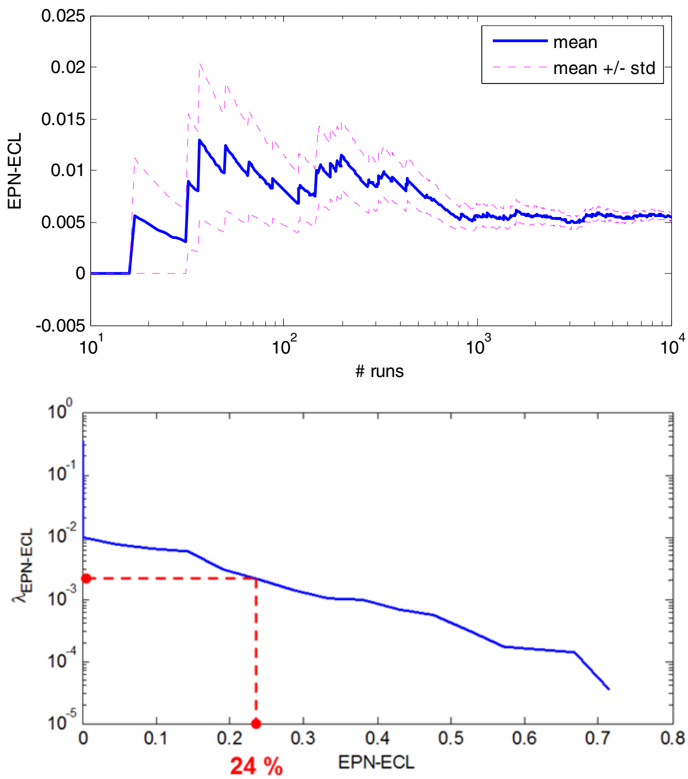

Figure 8: Moving average μ, μ+σ, μ-σ (up) and MAF (down) curves for ECL

Figure 10 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 identified 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.

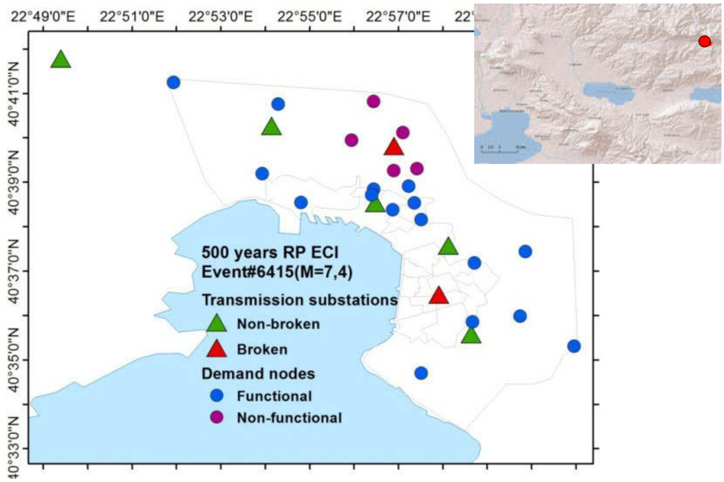

Figure 9: Electric power network damages for an event (#6415 M=7.4, R=40km) that corresponds to ECL with Tm=500 years

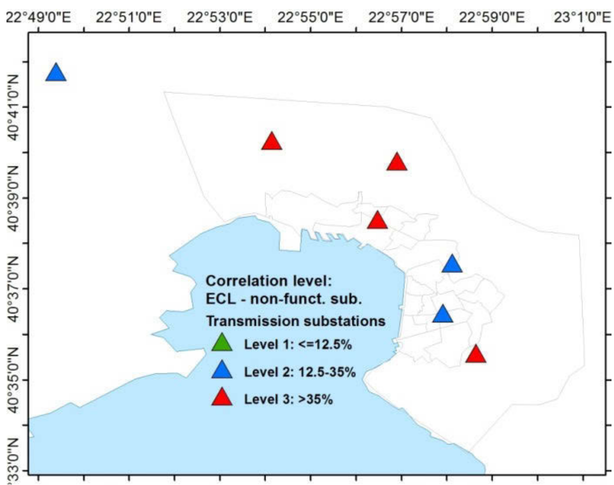

Figure 10: Correlation of non-functional transmission substations to electric power network connectivity loss

9.4 Water Supply System

Figure 11 shows the moving average (mean) curve for Water Connectivity Loss (WCL) 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. Figure 11 shows the

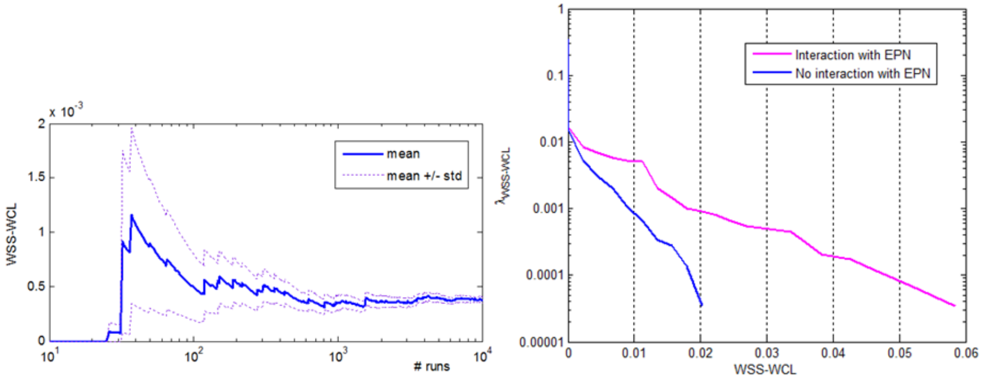

Figure 11: Moving average μ, μ+σ, μ-σ curves for WCL (left) and MAF curves with and without interaction with electric power netwrok (EPN) (right)

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 λ=0.001 (Tm= 1000 years) when the connections of water pumping stations to EPN are included in the analysis.

Figure 12 shows the level of correlation between the WCL and damages in pipelines as well as the non-functional EPN substations supplying the water

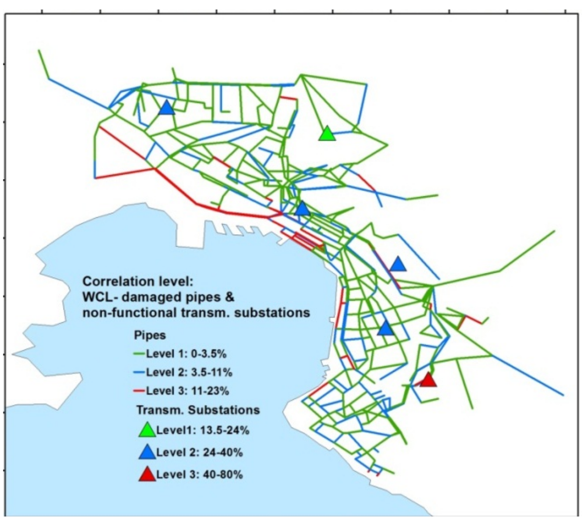

Figure 12: Correlation of damaged pipes and non-functional EPN transmission stations to water network connectivity

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 S-E part of the city, where several pumping stations (connected to EPN) are located. Figure 13 shows an example of the expected distribution of damages for an event that corresponds to connectivity loss (WCL=1.4%) with mean return period Tm=500 years. 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.

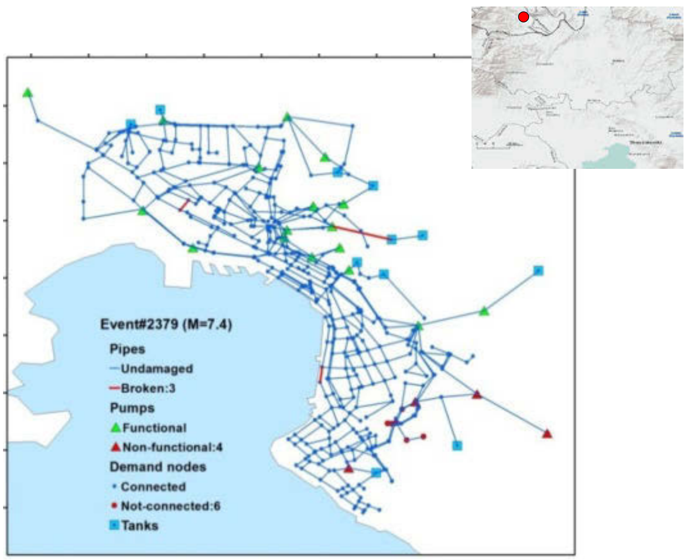

Figure 13: Water supply system damages for an event (#2379, M=7.4, R=72km) that corresponds to WCL with Tm=500 years

9.5 Buildings

Figure 14 shows the moving average (mean) curves as well as the mean+stdv and mean-stdv curves for expected deaths. 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. 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. In other words it is not a scenario-based event, which will produce a completely different image. Similar curves and results are derived for injuries and displaced people (in bad and good weather conditions).

Figure 14 also shows the MAF of exceedance curves for deaths (as percentages of the total population). The expected deaths for λ=0.002 (return period Tm=500 years) are 201. The distribution of building damages for an event that corresponds to this return period of deaths is shown in Figure 16. Similar maps can be obtained for casualties and displaced people. For this event, the estimated losses are: 2,248 collapsed and 16,634 yielding buildings, 201 deaths, 492 injuries, 180,000 (in good weather) and 288,000 (in bad weather) displaced people. Figure 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.

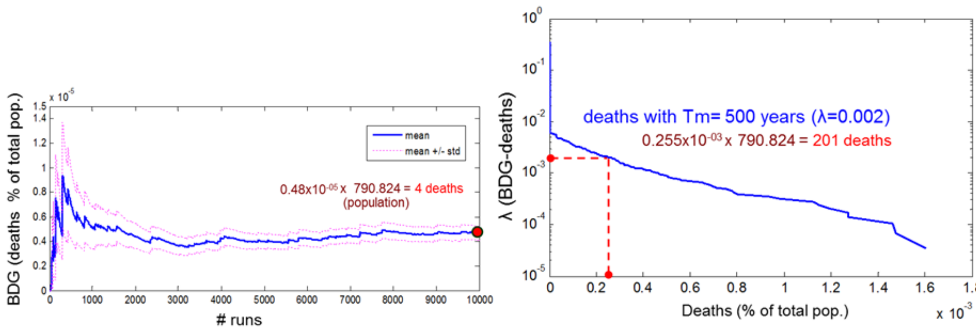

Figure 14: Moving average μ, μ+σ, μ-σ (left) and MAF curve for deaths (right)

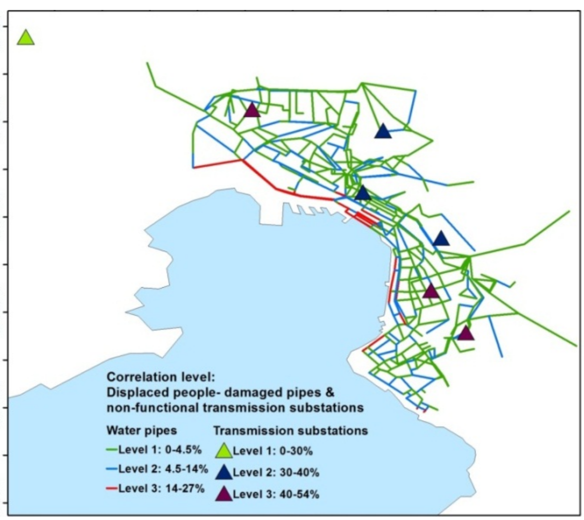

Figure 15: Correlation of damaged EPN and WSS to displaced people

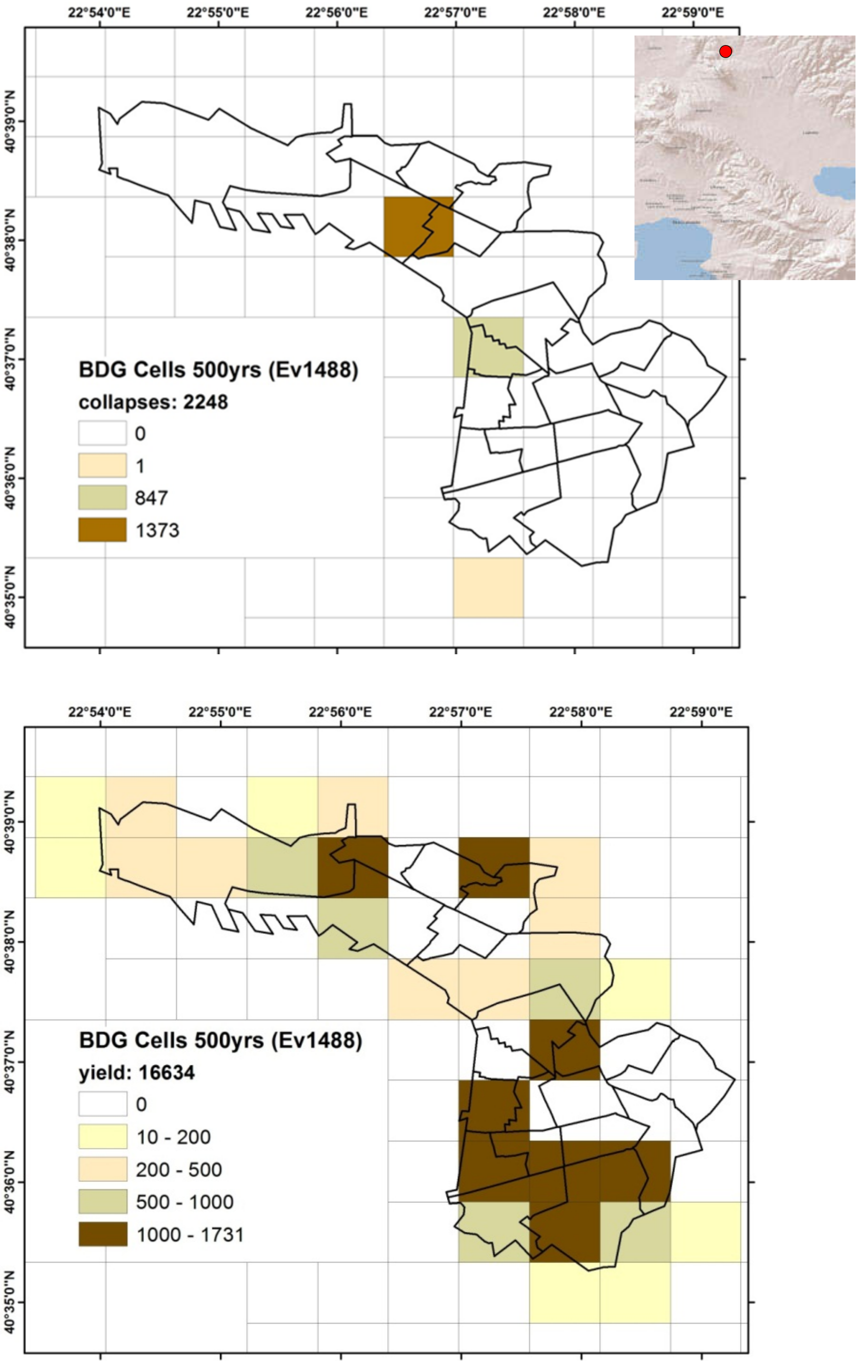

Figure 16: Distribution of estimated damages (collapsed and yielding buildings) into cells of the study area for an event (#1488, M=5.5, R=24 km) that corresponds to death rate with Tm=500 years

9.6 Road Network

Figure 17 shows the moving average (mean) curves for Simple Connectivity Loss (SCL) and Weighted Connectivity Loss (WCL), 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 Traffic Analysis Zones (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 the moving average is stabilized.

Figure 18 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. The same figure compares the estimated MAF of exceedance curve for SCL and 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 (λ=0.002). As an example the WCL is increased from 20% to 33% for λ=0.001 (Tm= 1000years) when the building collapses are included in the analysis.

Figure 19 and Figure 20 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 identified in relation with their contribution to the connectivity loss of the network. 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 centre of the city, where the vulnerability of buildings (mostly build with the oldest seismic code of 1959) is

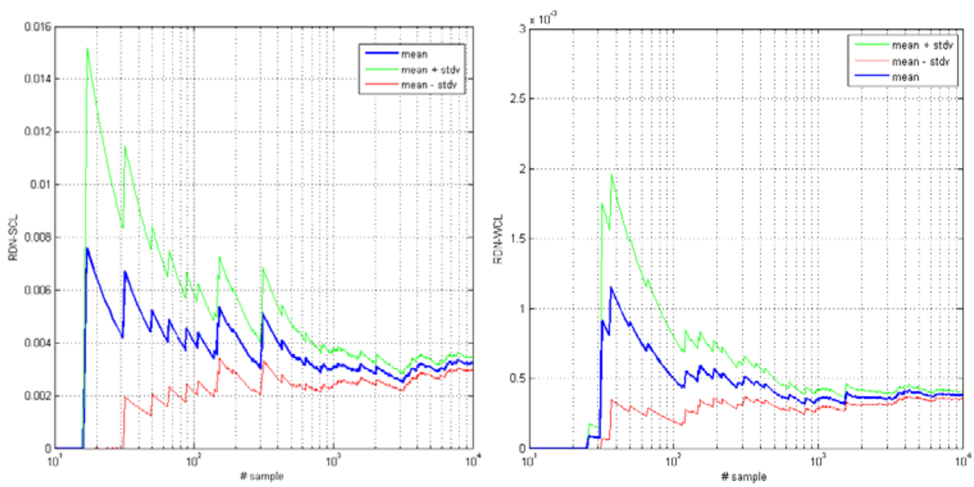

Figure 17: Moving average μ, μ+σ, μ-σ curves for SCL (left) and WCL (right)

higher and the road to building distance is shorter. Several road segments in the city centre 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.

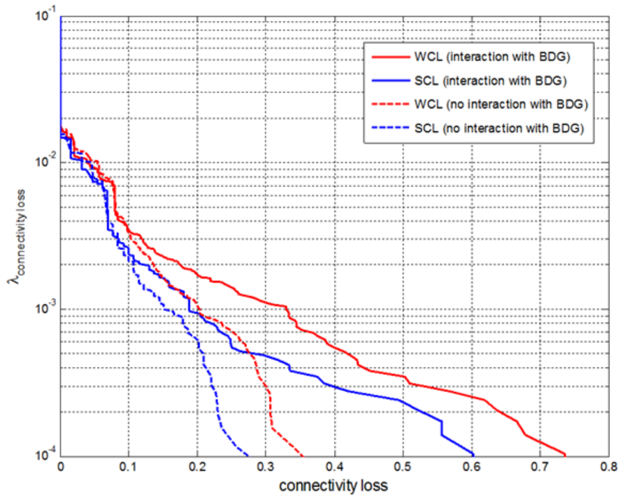

Figure 18: MAF curves for simple (SCL) and weighted (WCL) connectivity loss with and without interaction with building collapses

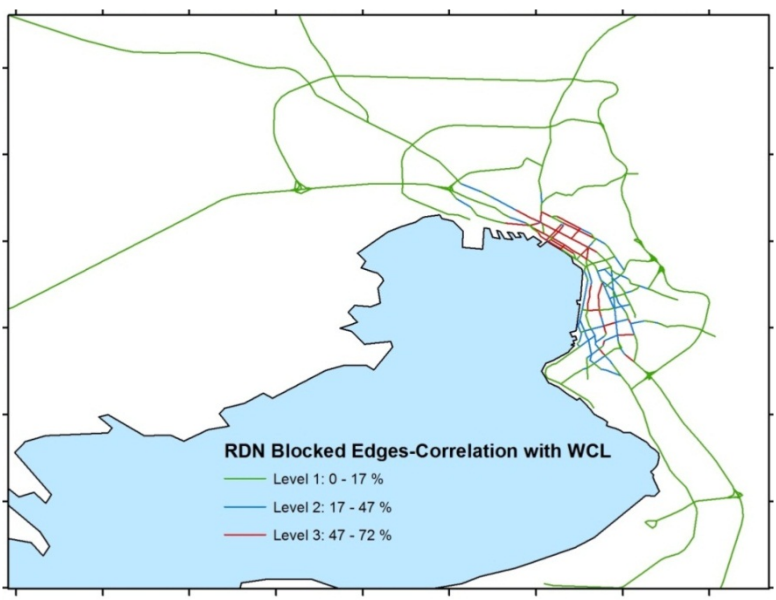

Figure 19: Correlation of blocked by buildings edges to road network connectivity (PI=WCL)

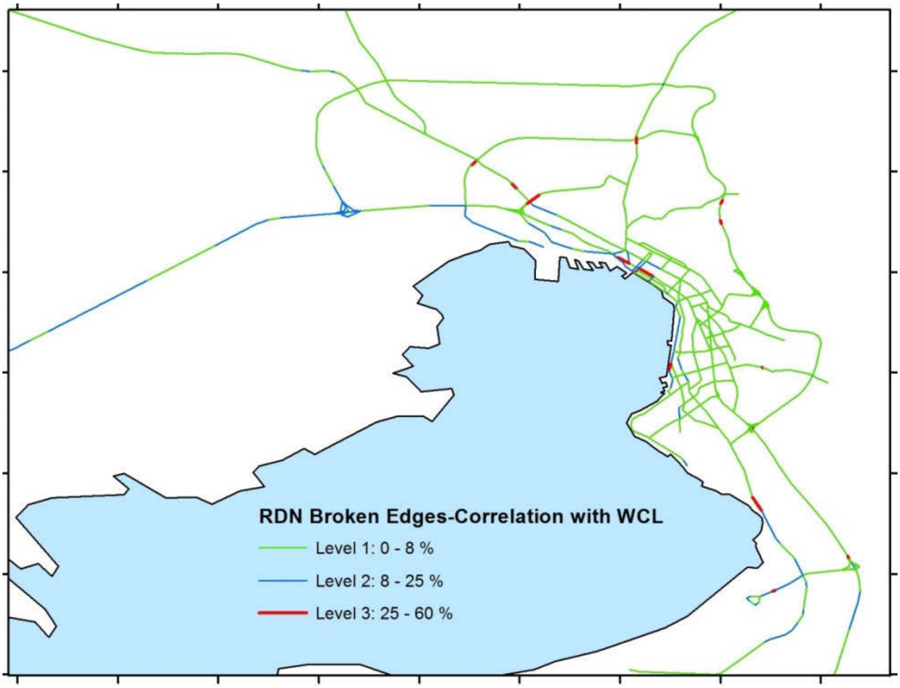

Figure 20: Correlation of broken edges (bridges) to road network connectivity (PI=WCL)

9.7 Shelter Needs and Accessibility 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 (section 7). In particular, a Shelter Needs Index (SNI) is estimated for each one of the 20 Sub City Districts (Figure 21) 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). In this way the Hot Spots" for shelter needs are identified using an interactive decision-support tool.

The estimated damages and losses of the road network provided input for the accessibility modelling to shelters and hospital facilities using isochrone-based and zone-based techniques. An example is given in Figure 22, where the accessibility to health facilities is estimated using the results of RDN over all runs.

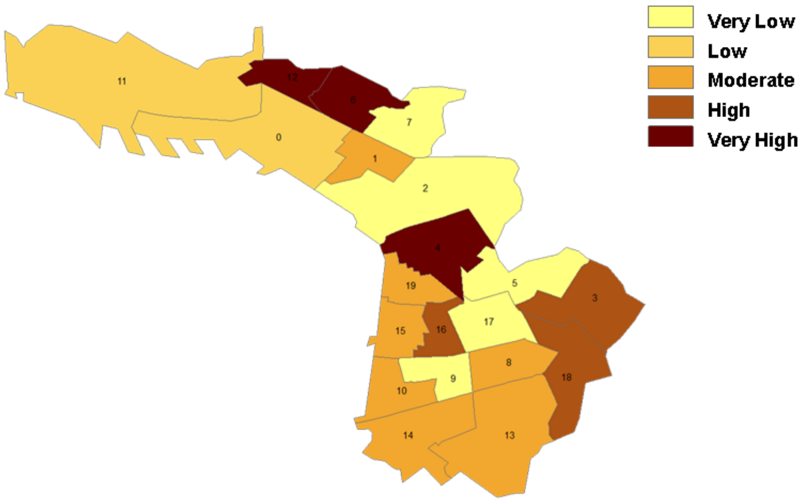

Figure 21: Ranking of Shelter Needs Index (SNI) for sub-city districts of Thessaloniki

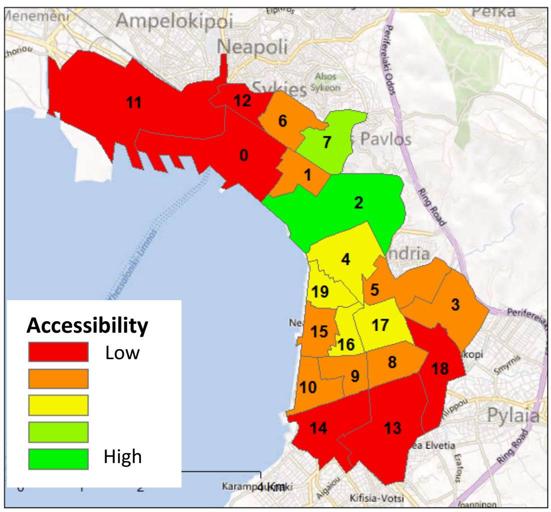

Figure 22: Accessibility to hospitals for Thessaloniki SCDs (zone based technique)

10 Conclusions

SYNER-G has developed a highly innovative and powerful methodology and tool for modern and efficient seismic risk assessment and management of complex urban or regional systems, lifelines and infrastructures. The basic idea is to account in the vulnerability and risk assessment the interdependencies and intra-dependencies (synergies) among various systems and networks, which is finally producing higher damages and losses. It is probably the first time that so many important components of this complex problem have been put together in a comprehensive and scientifically sound way. The whole methodology and tools have been applied and validated in different case studies of variable typology and complexity.

Several sources of epistemic and aleatory 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. The next step of the SYNER-G development is to tackle this issue and to make the whole software package more friendly and easily usable by end users.

11 Acknowledgements

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