JRC TECHNICAL REPORT

Pan-European Seismic Risk Assessment

*A proof of concept using the **E**arthquake **L**oss **E**stimation **R**outine (ELER)*

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Abstract
One of the key objectives of the new EU civil protection mechanism is an enhanced understanding of risks the EU is facing. Developing a European perspective may create significant opportunities of successfully combining resources for the common objective of preventing and mitigating shared risks. Risk assessments and mapping represent the first step in these preventive efforts. The EU is facing an increasing number of natural disasters. Among them earthquakes are the second deadliest after extreme temperatures. A better-shared understanding of where seismic risk lies in the EU is useful to identify which regions are most at risk and where more detailed seismic risk assessments are needed. In that scope, seismic risk assessment models at a pan-European level have a great potential in obtaining an overview of the expected economic and human losses using a homogeneous quantitative approach and harmonized datasets. This study strives to demonstrate the feasibility of performing a probabilistic seismic risk assessment at a pan-European level with an open access methodology and using open datasets available across the EU. It aims also at highlighting the challenges and needs in datasets and the information gaps for a consistent seismic risk assessment at the pan-European level. This report constitutes a "proof of concept" that can complement the information provided by Member States in their National Risk Assessments. Its main contribution lies in pooling open-access data from different sources in a homogeneous format, which could serve as baseline data for performing more in depth risk assessments in Europe.

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CONTENT

1 INTRODUCTION

Earthquakes are among the most common natural events in Europe. Over the 35-year period between 1980 and 2014, earthquakes were the second deadliest natural events after extreme temperatures causing more than 33 000 deaths and 62 billion Euros worth of damage (source: EMDAT[1]) in particular in the Mediterranean area (Figure 1). Earthquakes represent a societal challenge in Europe as well as globally necessitating practical and operational solution for mitigating risk and reducing losses. This is achievable though earthquake risk assessment.

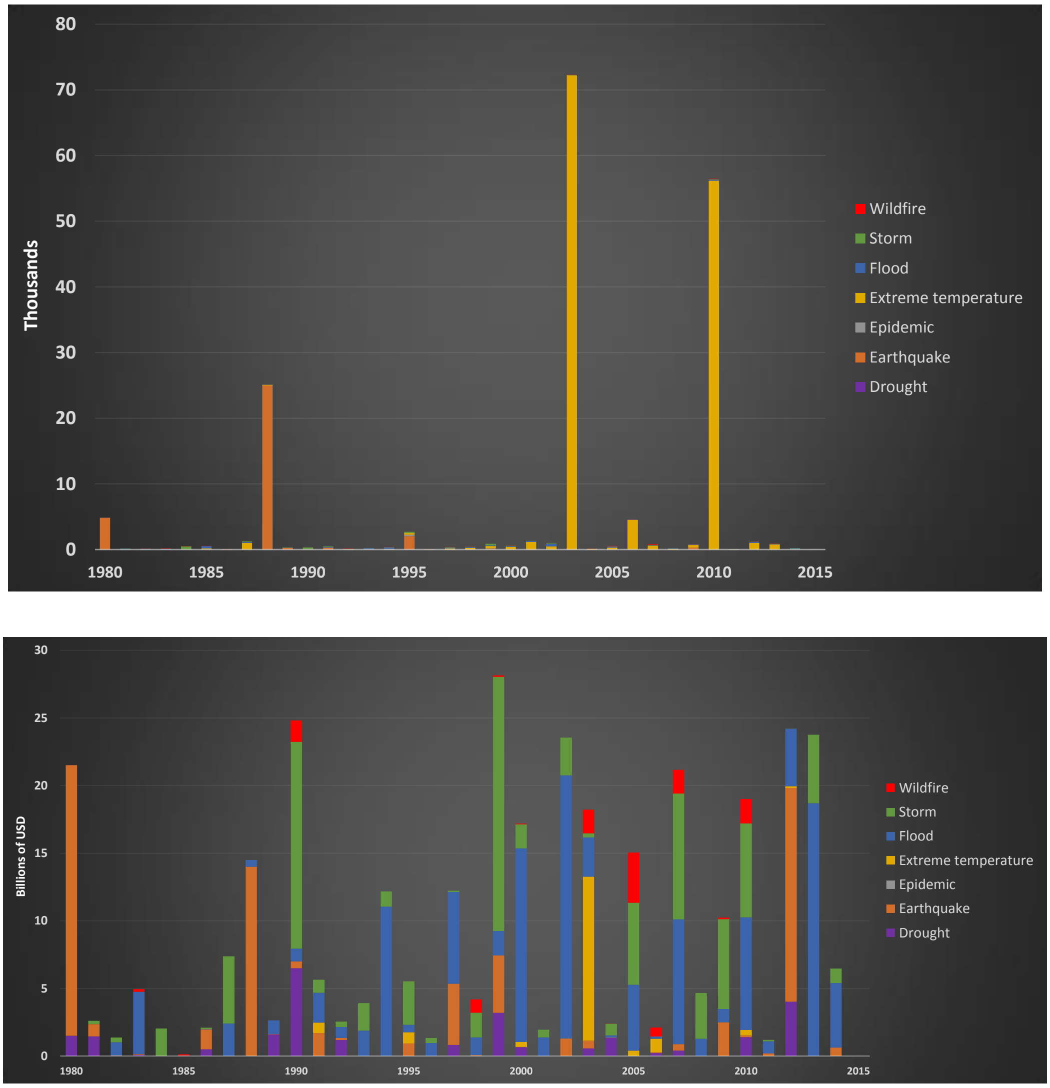

Figure 1. Human (a) and economic losses (b) between 1980 and 2014 due to natural disasters in Europe extracted from EMDAT database.

[1] http://www.emdat.be/database- The economic and human losses reported here may be underestimated due to the fact that EMDAT database focuses on the response phase of the disaster management by considering losses reported within three months after the event.

Earthquake risk assessment is considered here as the likelihood of human and economic losses resulting from the exposure and the vulnerability to seismic hazard. Human losses are usually measured in terms of expected casualties (deaths and injuries), while economic losses are measured in terms of direct economic loss (repair and replacement costs) and indirect economic loss (declines in output or revenue as a consequence of direct economic loss or disaster impacts).
This definition implies that the evaluation of earthquake risk is dependent on three components: 1) the earthquake hazard, 2) the inventory of assets at risk (i.e. human and physical exposure) and 3) the vulnerability of the exposed assets to seismic hazard. Hence, earthquake risk assessment is a complex exercise involving the assimilation of geological, seismological, engineering, demographic and economic data within a risk assessment model. Earthquake models are generally conceived on the basis of two different approaches: deterministic or probabilistic. The two methods are briefly described in the following section including

1.1 PROBABILISTIC VERSUS DETERMINISTIC EARTHQUAKE MODELS

Kijko et al. (2003) outline the main differences between deterministic and probabilistic approaches for the assessment of earthquake damages and losses as follows:

- The deterministic approach generally considers a user-chosen scenario known as the “worst case scenario” or the “maximum credible earthquake” and estimates the ground motions and the expected damages and losses. Early techniques in the insurance industry employed this modeling approach which is used to estimate the Probable Maximum Loss (PML). PML is relevant to determine the size of reserves that, for example, insurance companies or a government should have available to buffer losses. In this study it is defined as the estimated loss that would occur for a given return period. The main advantage of the deterministic approach is that it provides a means for the consideration of an extraordinary earthquake and consequently unusual set of damages/losses.
- The probabilistic approach considers the hazards from “all” possible seismic sources that may impact a particular site and how often the events may occur. It estimates the probability per year of exceeding certain levels of ground motion attributed to a seismic source. Probabilistic earthquake risk assessment models provide the probability distributions of expected losses obtained from a representative ensemble of scenarios (Kunreuther, and Roth, 1998). They can be viewed as inclusive of all deterministic events with a finite probability of occurrence. Most of the currently used models of earthquake risk assessment are, by their nature, probabilistic, and provide the assessments of the probability distributions of expected losses obtained from a representative ensemble of scenarios (Kunreuther, and Roth, 1998). This approach allows computing the Average Annual Loss (AAL), which corresponds to the summation of products of event losses and event occurrence probabilities for all of the stochastic events in a loss model. AAL is the expected average loss per year considering all the events that could occur over a long time frame. It is a compact metric with a low sensitivity to uncertainty (UNISDR, 2015). This metric can provide an insurance program with a basis for calculating the amount of premium needed to cover each of the buildings it insures. The consideration of uncertainty described through random variables, by their probability distribution, represents an interesting feature of this probabilistic approach. In contrast to deterministic approaches, it represents one of its main advantages (Kirchsteiger, 1999). The drawback of the probabilistic approach lies in the complexity of the analysis, the large data

requirements and the assumptions used. The results are expressed as prognostic estimations of potential losses in the future and hence difficult to communicate to decision-makers.

Despite their different assumptions, it is not simple to establish a strict division of earthquake risk assessment models into deterministic and probabilistic categories. It is often the case that deterministic risk assessment models include random variables or various probabilistic elements. Besides, many deterministic risk assessment models rely on probabilistic earthquake hazard analysis in order to select the earthquake rupture that is contributing the most to the hazard or loss, conditional on a given return period. The two approaches are complementary in providing additional insights into the seismic risk problem: “deterministic events can be checked with a probabilistic analysis to ensure that the event is realistic, and probabilistic analyses can be checked with deterministic events to see that rational, realistic hypotheses of concern have been included in the analyses” (McGuire, 2001).

The choice of an approach will depend on the purpose of the seismic risk assessment: financial planning of earthquake losses, disaster risk mitigation, retrofit design, etc. The more quantitative the decision to be made, the more appropriate is the choice of a probabilistic approach.
Other factors enter into modelling choices such as data availability and data access, the degrees of complexity and usability and whether the software packages are proprietary, open-access or open-source. In the following section, some of the available open-access seismic risk modelling platforms are presented including their main features and the principal criteria that need to be considered before deciding on the choice of a particular software. For a comprehensive review of open-access and open-source multi-hazard risk modeling software, readers are referred to the following reports:

1- Review of Open Source and Open Access Software Packages Available to Quantify Risk from Natural Hazards, (World Bank, Global Facility for Disaster Reduction and Recovery, 2014),
2- GEM technical report (Part 1) (Crowley et al., 2011).

1.2 OPEN-ACCESS AND OPEN-SOURCE SEISMIC RISK MODELLING PLATFORMS

Seismic risk modelling involves sophisticated sub-models that call for multi-disciplinary expertise in fields such as seismology, geotechnical and structural engineering and economics. In some cases, they also comprise a Geographic Information System (GIS) module. Therefore, they tend to be costly to produce and as a result, the majority of the models developed up to now is commercial or closed in nature. The fact that the users are not able to control the underlying methods causes some serious concerns about the models dependability especially when several models produce significantly different estimates of risks using the same input data (Porter and Scawthorn, 2007). In a paper published in 2007, Kishi (2007) highlighted the differences in estimated industry losses from Hurricane Katarina obtained by three principal risk assessment models: the differences ranged about a factor of three going up to a factor of five over the space of a few weeks (Mina et al., 2008). Lack of transparency and accessibility to risk analysis models is driving the users’ community and mostly researchers to opt for open-access and if possible open-source software tools that they can explore, enhance and even customize. The need for transparency has been a major driver for the development of open-access and some open-source earthquake risk models through partnerships and collaborations such as the AGORA[2], (The Platform for Open Risk Analysis), GEM[3] (Global Earthquake Model) and CAPRA[4] (Comprehensive Approach for Probabilistic Risk Assessment).

Some available open access state-of-the-art tools tailored for earthquake risk assessment are: CAPRA GIS- Earthquake module, EQRM, HAZUS-MH earthquake module, InaSafe-Earthquake, MAEviz/mHARP, OpenQuake, ELER, RiskScape-Earthquake, SELENA.

The purpose here is not to review all these tools but to outline their main methodological characteristics and propose some elements for consideration when selecting a software package for earthquake risk assessment.

1.2.1 CAPRA GIS

CAPRA-GIS is a geographic information system developed in the context of CAPRA and oriented to perform probabilistic risk calculations. The CAPRA Program is a modular, free platform for probabilistic risk assessment of natural hazards. It uses a multi-hazard risk approach to determine conjoint or cascading risk (e.g. an earthquake is assessed in terms of shaking ground. Secondary hazards include tsunamis and landslides, whose effects include the run-up height (maximum height above sea level).
The method allows calculating both event-based set probabilistic and scenario-based risk expressed in terms of physical damage, direct economic and human losses. The hazard module (CRISIS 2007) defines the frequency and severity of the earthquake hazard at a specific location. This module allows estimating the hazard associated with all possible events that can occur or to a group of selected events, or even to a single relevant event. It provides the probable maximum value of the parameter characterizing the seismic intensity for different exceedance rates or return periods. The vulnerability module (ERN-Vulnerabilidad) allows computation of fragility functions that are essentially user driven. Instead of using qualitative scales as in the case of damage states, numerical scales are used to define loss, like for example, the Mean Damage Ratio (MDR) (i.e. ratio of the repair cost of a building to the economic value), with a direct use in probabilistic risk and loss calculations (Marulanda et al., 2013).

Advantages of CAPRA-GIS include:

- Its open-access nature and ability to handle sequential effects of earthquakes.
- The possibility to perform both a full probabilistic risk assessment and event-based loss and damage assessments.
- Variability and uncertainty are handled well.
- Since this quantification of risk follows an established and well document methodology, users are enabled, with a common language, to measure, compare or aggregate expected losses from various hazards over the same area.

[2] http://www.preventionweb.net/english/professional/contacts/v.php?id=3589

[3] http://www.globalquakemodel.org/

[4] http://www.ecapra.org/about

- Besides, the availability of a built-in GIS interface with basic functions facilitates the display and analysis of the results.

The main drawbacks are:

- The difficulties in inputting hazard data from other programs than CRISIS 2007 module. The output of this module is an .ame file type (.ame from amenaza that is hazard in Spanish) which includes multiple grids on the area of study, for the different possible intensity parameters of the seismic hazard. This particular format is difficult, if not impossible to produce using another program.
- The damage distribution is not calculated directly and only the MDR is available (World Bank, Global Facility for Disaster Reduction and Recovery, 2014).
- There is no formal user manual.

1.2.2 HAZUS-MH

The Hazards U.S. Multi-Hazard methodology was developed by the United States Federal Emergency Management (FEMA) for the assessment and mitigation of losses from earthquakes, hurricanes and floods. The software was originally developed for the United States to account for earthquakes (ground-shaking, ground failure, liquefaction, rupture, landslide (Kircher et al., 2006). Later work has included flood and tropical storms. HAZUS-MH combines earthquake hazard data (e.g. shake maps), engineering information on structures response to shaking and GIS for mapping the hazard data and the economic loss estimates. Both deterministic and probabilistic approaches are implemented. The loss assessment methodology consists of three main components:

- Potential Earth Science Hazard (i.e. ground motion, ground failure and tsunami/seiche)
- Direct physical damage (i.e. the probability of damage to general building stock through the use of fragility curves and building capacity curves)
- Induced physical damage (e.g. damage caused by inundation, fires following earthquake)
- Direct economic loss (e.g. repair and reconstruction costs and loss of building contents)
- Indirect economic loss (e.g. business interruptions, lost jobs)
- Social losses (e.g. estimated casualties, shelter needs, displaced households)

The main advantages of HAZUS-MH are:

- The default input data packaged with the software and the default mapping schemes tailored to the US context. The building inventory for the US comprises 36 different structural building classifications (called building type in HAZUS-MH).
- The software includes a very detailed technical and user manual and the methodology is very well documented in many reports and scientific papers.
- It is one of the few open access earthquake that includes a module for the assessment of indirect economic losses based on Input-Output models.

Disadvantages of HAZUS- MH include:

- It uses a deterministic and event-driven model and can only estimate the impact of a single event, i.e. it cannot produce probabilistic risk estimates.
- Labour intensive input data for applications at local level or outside the US: while the use of default data requires minimal effort by the user, modification of the defaults or input of

local-level data requires significant expertise in GIS, databases and in other aspects of the system being modified (Maheshwari, 2007).
- The format of damage functions is not readily suitable for visualisation.
- Although free, the software requires a commercial GIS software (ArcGIS) to operate.

1.2.3 OPENQUAKE

OpenQuake is the result of a recent development comprising a suite of open-source software for seismic hazard and risk assessment. The OpenQuake project is a collaborative effort initiated by the GEM community (Pinho, 2012). OpenQuake currently provides a web-based risk assessment platform offering five state-of-the-practice calculators for assessing the damage and loss due to earthquakes (Silva et al., 2014):

- The scenario risk calculator: for computing losses and statistics due to single scenario earthquake for a collection of assets,
- The scenario damage assessment: for estimating damage distribution due to a single scenario earthquake for a collection of assets,
- The probabilistic event-based risk: for computing the probability of losses and loss statistics for a collection of assets based on the probabilistic hazard. Loss statistics, i.e., the mean loss and standard deviation of loss for both ground-up losses and insured losses across all realizations, are calculated for each asset. Mean loss maps are also generated by this calculator, describing the mean ground-up losses and mean insured losses caused by the scenario event for the different assets in the exposure model.
- The classical PHSA - based risk: for calculating the probability of losses and loss statistics for single assets based on the probabilistic hazard. Loss curves and loss maps can be calculated for five different loss types: structural losses, non-structural losses, contents losses, downtime losses, and occupant fatalities. The main results are loss exceedance curves for each asset, which describe the probability of exceedance of different loss levels and loss maps for the region, which describe the loss values that have a given probability of exceedance over the specified time period.
- The benefit-cost ratio: is a decision support tool for comparing the long-term benefits of seismic retrofitting/strengthening measures against the upfront costs. This calculator can explicitly account for both direct losses associated with damage to structural components, non-structural components and building contents, and indirect losses associated with the loss of life and downtime/business interruption. The calculator also accounts for the time-value of future benefits by discounting them by a given rate of interest.

The main advantages of OpenQuake are:

- The well documented source code and the comprehensive book providing an explanation of scientific basis and the methodologies (Crowley et al., 2011),
- The availability of wide range of hazard and risk analysis tools,
- It currently offers the most in-depth probabilistic analysis of any of the reviewed software packages for earthquake, accounting for classical PSHA as well as event-based PSHA (World Bank, Global Facility for Disaster Reduction and Recovery, 2014)

The limitations of OpenQuake are:

- The absence of a user-friendly and intuitive interface for running the analysis and displaying the results,

- It considers only direct physical damage. Indirect losses cannot be assessed using the current version of OpenQuake.

1.2.4 ELER

The Earthquake Loss Estimation Routine (ELER) was developed under the NERIES FP6 project (2006-2010) for rapid estimation of earthquakes damages and casualties. The loss estimations is conducted under three levels of sophistication (namely level 0, 1 and 2). The ground motion estimation methodology is common to all three levels. The choice of computing earthquake losses using one of the three levels of calculation is essentially controlled by the availability of input data (Erdik et al., 2010). The methodology employs the following steps:

- In the hazard module, for a given earthquake magnitude and epicenter information, spatially distributed intensity and ground motion parameters (Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Spectral Acceleration (SA), Spectral Displacement (Sd)) are estimated through region specific ground motion prediction equations and gridded shear wave velocity information.
- Level 0 module can be run using intensity-based maps (i.e. shake maps). The casualty estimation is done utilizing regionally adjusted intensity casualty or magnitude-casualty correlations based on the LandScan population distribution inventory.
- Level 1 module is also based on seismic hazard intensity distribution maps. The intensity based empirical vulnerability relationship is employed to estimate the number of damaged buildings and associated losses. The casualty estimation is derived from the number of damaged buildings.
- Level 2 module corresponds to the highest sophisticated level in the loss estimation methodology. The analysis is based on ground motion maps. The number of damaged buildings and associated casualties are obtained using analytical fragility relationships and building damage related causality fragility models, respectively. The methodology is similar to HAZUS-MH. The spectral acceleration-displacement-based vulnerability assessment methodology is utilized for the building damage estimation. The casualty estimation is done through number of damaged buildings using HAZUS99 and HAZUS-MH methodologies.

The advantages of ELER are:

- The HAZUS, EMS'98 (Grünthal, 1998), and RISK-UE (2001-2004) building taxonomies are used as the default main classification systems in the development of ELER. However, the software is structured in such a way that a building inventory can be accommodated in terms of any classification system as long as the vulnerabilities associated with each building type are defined by the user.
- The outputs are in the form of a shapefile can be manipulated with GIS editors for custom visualisation and further analysis.
- The software is tailored to scenario based risk analyses as well as for quasi-real time rapid earthquake loss assessment.
- A default building inventory (used in Level 1 analysis) corresponding to an approximated European database of number of buildings and their differentiated structural types in each EU country is available within the software aggregated to 150 sec arc grids.

The drawbacks of ELER are:

- There is not a command line interface if a user would like to perform automated, scheduled or event triggered runs (Crowley et al., 2010)
- The platform allows calculating damage/loss maps that are conditional on the hazard with a given return period: it reads and provides losses using a single probabilistic seismic hazard map at a time, which makes it difficult to perform a fully probabilistic risk assessment.

The following table summarizes some of the features of the four seismic risk assessment packages discussed in this study. It gives quick insights into the technical/scientific characteristics that are generally considered when choosing a software.

Table 1.Summary table of the four software packages for earthquake risk assessment

	Open Source	Programming language	Supported platform	Modelling approach	Direct economic losses	Indirect economic losses	Human losses	Applicability region
CAPRA-GIS	Yes	Visual Basic.NET	Windows	.Deterministic even-based .Probabilistic	Yes	No	Yes	. Latin-America . User defined
HAZUS-MH	No	VB6, C++	Windows (only US English version)	.Deterministic even-based	Yes	Yes	Yes	. US . User defined
OpenQuake	Yes	Python	.Windows (x64 .Linux .Mac OS X	.Deterministic even-based .Probabilistic	Yes	No	Yes	. User defined
ELER	No	Matlab	.Windows (x64) .Linux (x86-64) .Solaris 64	. Deterministic event-based	Yes	No	Yes	. Euro-Mediterranean . User defined

1.3 SEISMIC RISK ASSESSMENT AT THE EUROPEAN AND GLOBAL LEVELS

The knowledge and understanding of seismic hazard and risk has advanced through a number of projects with European and Global scope.

The Global Seismic Hazard Assessment Program (GSHAP) (Giardini et al., 1999) is the first global hazard map of peak ground acceleration for a return period of 475-year. Recently, in the framework of the Global Assessment Report (GAR) 2015 (UNISDR, 2015), a fully probabilistic seismic hazard assessment at global level was developed and used for a probabilistic risk assessment estimating the order of magnitude of potential losses.

At the European level, several initiatives have focussed on different components of seismic risk. The SHARE[5] (Seismic Hazard Assessment in Europe) project (2009-2013) delivered a European wide probabilistic seismic hazard assessment. The project produced more than sixty time-independent European Seismic Hazard Maps (ESHMs) spanning spectral ordinates from PGA to 10 seconds and exceedance probabilities ranging from 10^{-1} to 10^{-4} yearly probability. The SYNER-G[6] (Systemic seismic vulnerability and risk analysis for buildings, lifeline networks and infrastructures safety gain) project (2009-2013) developed an innovative methodological framework for the systemic assessment of physical as well as socio-economic seismic vulnerability at urban and regional level. The NERA[7] (Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation) project (2010-2014) aimed at integration seismic and engineering infrastructures to establish an effective network of European research infrastructures for earthquake risk assessment and mitigation. Building on past-achievements, the project identified key players in European building inventory collection and summarized the state-of-the-art knowledge of building inventory data in Europe. RISK-UE project (2001-2004) (Mouroux and Brun, 2006) involved the assessment of earthquake scenarios based on the analysis of the global impact of one or more plausible earthquakes at city scale, within a European context (Mouroux and Brun, 2006). A comprehensive building type classification for Europe that incorporated the characteristic features of the European building taxonomy was also developed in that project.

In terms of seismic risk, the fully probabilistic seismic risk assessment produced as part of the GAR 2015 is the first example of globally, publically available information on loss levels determined for five return periods (250, 475, 975, 1500 and 2475-year) and on AAL calculated for each country (Figure 2). The GAR 2015 is the first of its kind to provide worldwide coverage of risk assessments for multiple hazards. The earthquake risk was calculated within the CAPRA-GIS platform, which is the risk modelling tool of the CAPRA suite (section 1.2)

The AAL values produced as part of the GAR 2015 are derived from proxies and expert judgment in cases where empirical data was absent. Hence, the results of the global seismic risk assessment are very sensitive to most of the variations in the input data and to the modelling assumptions and cannot be considered or exploited at local scale.

Despite all the previously cited EU projects and the wealth of knowledge and data generated by research in the field of seismic risk, none of the initiatives succeeded in assessing seismic risk at the European level. A possible explanation could be related to the challenges in combining different datasets with different formats and levels of details. In addition, to the heterogeneity in the dataset, the availability of exposure data including the value of the exposed assets remains a critical information gap.

[5] http://www.share-eu.org/node/61

[6] http://www.vce.at/SYNER-G/files/project/proj-overview.html

[7] http://www.nera-eu.org/

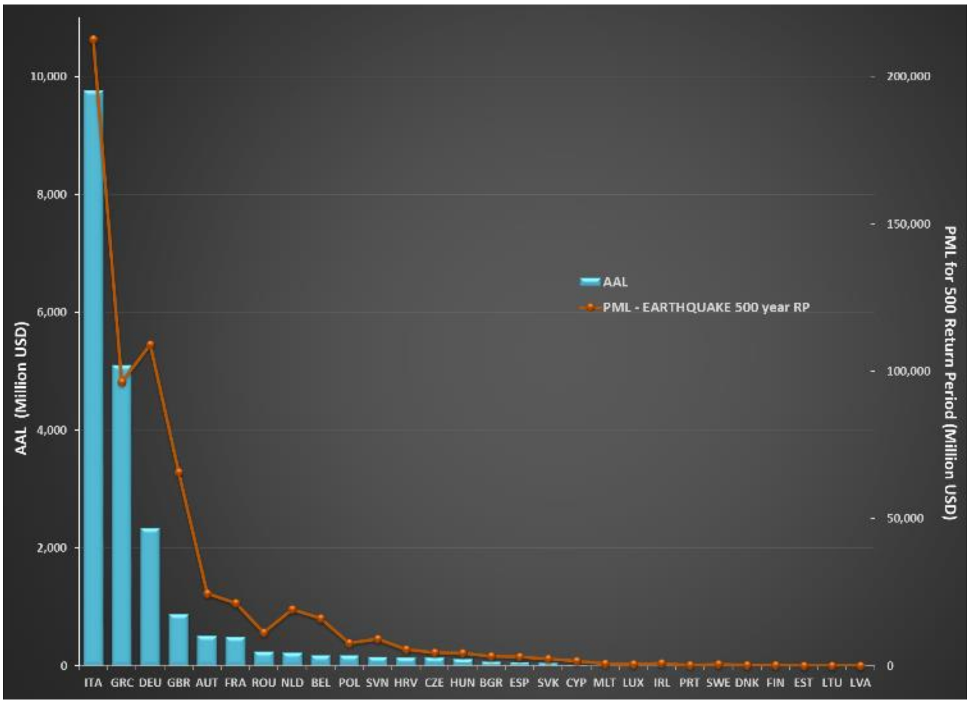

Figure 2. Average Annual Loss (AAL) and Probable Maximum Loss (PML- for 500 years return period) associated with earthquake hazard in European countries, assessed as part of the GAR 2015 (UNISDR, 2015).

1.4 OBJECTIVE OF THIS STUDY

The new EU civil protection mechanism[8] calls for an enhanced understanding of risks over the EU territory. This is the basis for a more effective disaster management and a starting point for developing contingency plans for a collective European response to major disasters. Risk assessment is "the building block" for developing strategic activities of disaster risk management. It requires the use of reliable methods, which can provide quantitative estimations of individual and coupled risks.

At present, the ranking of the typologies of risks affecting the EU can hardly be made because the available scenarios and risk assessment in general are often qualitative or semi-qualitative (e.g. ESPON project); they are related to one reference event and rarely account for the related uncertainties. "Moreover different types of risks (as volcanic, fast mass movements, floods, earthquakes) are often estimated using different procedures so that the produced results are not comparable" (Marzocchi et al., 2009). Risk assessment models based on metrics such as the PML or the AAL can be useful at many levels. In addition to the possibility of comparing risks from multiple hazards, risk assessment models can help i) evaluating the amount of acceptable loss, ii) assessing the necessary investments in disaster risk reduction measures (e.g. structural retrofitting), iii) tracking risk-based loss information, and iv) measuring progress against targets set out in the Sendai Framework for Disaster Risk Reduction (Corbane et al., 2015)

[8] Decision No 1313/2013/EU of the European Parliament and of the Council of 17 December 2013 on a Union Civil Protection Mechanism, *Official Journal of the European Union*, L (347), 20.12.2013

In an overview of disaster risks in the EU (European Commission, 2014) based on National Risk Assessment reports provided by 18 Member States in the context of the new Civil Protection Mechanism legislation (Art.5), 9 countries have identified seismic hazards and their socio-economic impacts as a great concern (i.e. Bulgaria, Cyprus, Czech Republic, Germany, Greece, Hungary, Italy, Romania, and Slovenia). By their very nature, earthquakes are unpredictable hazards that occur irrespective of national borders. The cross-border dimension of the earthquake risk is correlated to the exposure of areas along the fault lines in the Eastern Mediterranean and the Black Sea regions. A better shared understanding of where seismic risk lies in the EU is useful to identify which regions are most at risk and where more detailed seismic risk assessments are needed. In that scope, seismic risk assessment models at a pan-European level have a great potential in obtaining an overview of the expected economic and human losses using a homogeneous quantitative approach and harmonized datasets.

This study strives to demonstrate the feasibility of performing a probabilistic seismic risk assessment at a pan-European level with an open access methodology and using open datasets available across the EU. The results of this work are not meant to support decision-making nor for establishing inter-country comparisons of seismic risk. Their main purpose is to assess the possibility of performing a probabilistic seismic risk assessment with advanced methods and datasets that could help in drawing attention to the areas where necessary refinements are required.

2 THE RISK ASSESSMENT METHODOLOGY

This chapter summarizes the methodological choices for investigating the feasibility of a probabilistic risk assessment at a pan-European level. Methods of data collection, preparation and analysis are discussed together with the assumptions and limitations of the selected approach.

At the time of writing, the most up-to-date and comprehensive seismic hazard model across Europe was the one provided in the context of the SHARE project. The project delivered a European wide probabilistic seismic hazard assessment (Woessner et al., 2015). The new reference European Seismic Hazard Map (Figure 3) displays the ground shaking (i.e. Peak Ground Acceleration) to be reached or exceeded with a 10% probability in 50 years, corresponding to an average recurrence of such ground motions every 475-year, as prescribed by the national building codes in Europe for standard buildings (although some countries do not use this return period for building codes, e.g. Spain). The values of expected ground shaking are in many areas higher than previously estimated and reach over 0.5 g (“g” standing for gravitational acceleration) in the areas of highest seismicity.

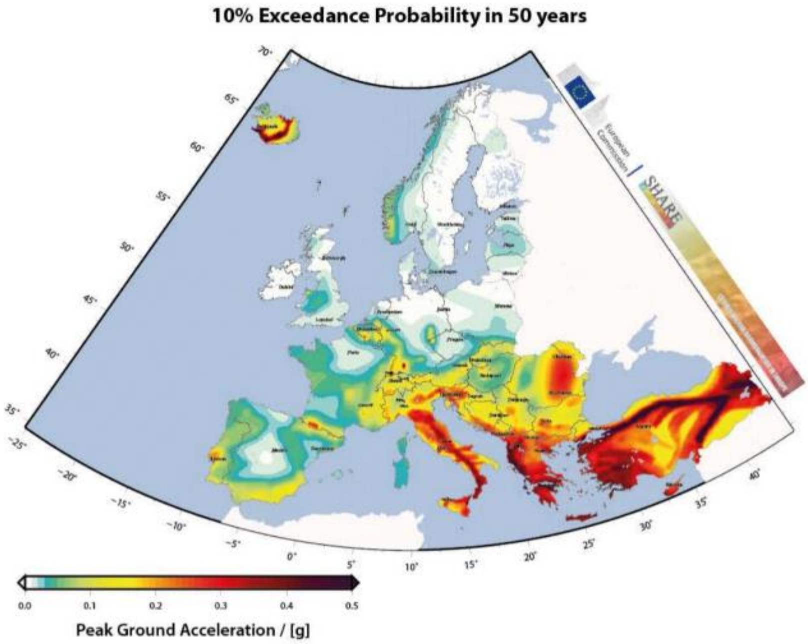

Figure 3. A European Seismic Hazard Map (ESHM) illustrating the probability to exceed a level of ground shaking in terms of the peak ground acceleration with a 10% probability in 50 years (corresponding to a return period of 475-year).

Hence, the natural choice was to perform the pan-European seismic risk assessment using the results from SHARE project, taking stock of experiences and knowledge and building on the outcomes of previous EU projects.

All of the four software packages briefly discussed in section 1.2 support a probabilistic risk analysis although the risk outputs are variable depending on the way in which the seismic hazard is modelled (see table 1.1 in Crowley et al., 2010). Due to the time constrains, and available computational resources, the OpenQuake tool was not chosen for this version.
HAZUS-MH is a pioneering application for seismic risk assessment with a user-friendly, GIS-based interface. The major obstacle for using this tool for an EU wide study is the flexible handling of data structures other than US. Any analysis for vulnerability, distribution of population, or building damage is based on a specific data scheme, which obviously differs from country to country (Kaveckis, 2011). Besides, the manual and complicated non-US data integration into the software was a prohibiting factor for using HAZUS-MH and thus not used in this experiment.
The CAPRA-GIS risk-modelling tool used for calculating the Global Risk as a contribution to the 2015 GAR was considered as a potential platform for implementing the experiment. However, at the current state the platform cannot accommodate external hazard data and thus not used in this analysis. In fact, we attempted to input the hazard data obtained from the SHARE project in the form of AME objects (formed by a collection of possible scenarios of occurrence of seismic hazard) but unsuccessfully as confirmed by the developers of CAORA-GIS.
ELER was the alternative software to CAPRA-GIS. Both codes are capable of running end-to-end scenario-based risk analysis and in outputting the results in the form of shapefiles for further processing and analysis. The latest version of ELER (v3.0) allows the user to input hazard maps,

and to define easily new building types and their associated vulnerability values. The most interesting feature of ELER was the availability of a building inventory data approximated from Corine Land Cover and population databases, in 150 sec arc grids for 27 countries in Europe. Although, the software was lacking a command line interface to perform scheduled or event triggered runs, it was considered as an optimal tool for running the experiment.

2.1 OVERVIEW OF THE RISK ASSESSMENT APPROACH USING ELER v3.0

The following flowchart (Figure 4) summarizes the three levels of analysis available in ELER for assessing earthquake losses (damage and causality) with increasing levels of sophistication (see section 1.2.4 for a brief description of the three levels of analysis). Both levels 1 and 2 include the calculation of direct monetary losses due to building damage. These tools allow for repair-cost estimations and specific investigations associated with earthquake insurance applications (PML and AAL estimations). The differentiation of the levels of analysis is mainly controlled by the availability of building inventory and demographic data (Erdik et al., 2010). As mentioned in the previous section, a regional-scale building inventory tailored for level 1 analysis was developed in the context of NERIES project. The availability of the 150 sec arc building inventory for 27 EU countries was the main motivation behind the selection of level 1 type analysis for modelling the seismic risk at the European level.

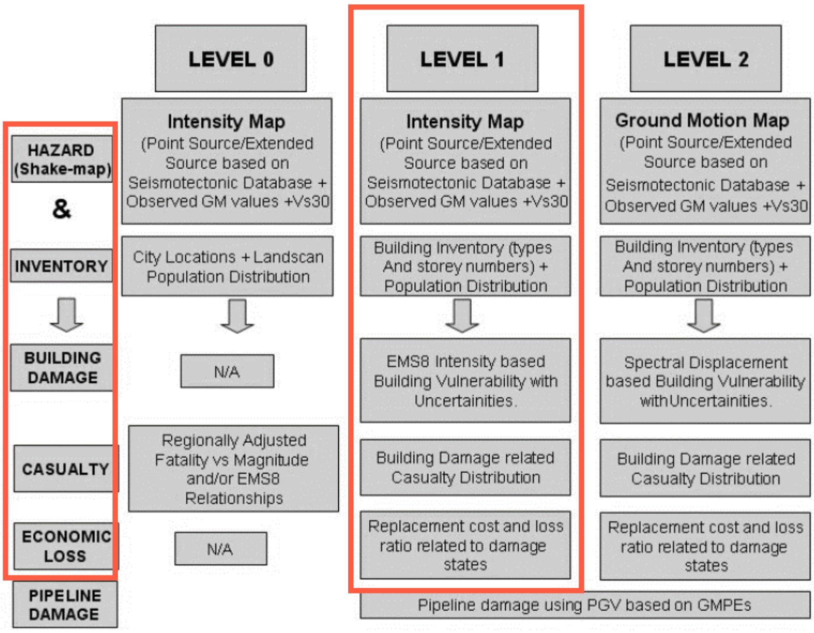

Figure 4. The three levels of earthquake loss assessment incorporated in ELER v3.0. The red rectangles correspond to the level of analysis implemented in this study.

Some background information on level 1 analysis is given hereafter. Technical details on the algorithms implemented in ELER can be found in the software manual[9].

[9] http://www.koeri.boun.edu.tr/depremmuh/eski/ELER/ELER_v3_Manual.pdf

2.1.1 HAZARD

Level 1 risk assessment engine relies on macroseismic damage estimation. The intensity based empirical vulnerability relationships of Giovinazzi and Logomarsino (2005) are utilised. Hence, for the representation of seismic hazard, an intensity based hazard map for a specific return period can be input into the system.

2.1.2 EXPOSURE

A grid based building database is specified for the study area as a shapefile containing the building distribution for each cell. It may also contain population data for each cell for computing human losses. The software requires to using the building inventory classified based on the Risk-UE building taxonomy (section 1.3). However, ELER is structured in a way that a building inventory can be classified in any classification system as long as the vulnerability/ductility indices are specified by the user. Besides, in ELER manual, a correspondence matrix between the PAGER, EMS98 and Risk-UE taxonomies is available in Annex 1 allowing an easy conversion from one typology to another.

2.1.3 VULNERABILITY

Intensity based empirical vulnerability functions are used for estimating building damage. They are based on a method referred to as macroseismic method originally developed by Giovinazzi and Lagomarsino (2005) from the definition provided by the European Macroseismic Scale (EMS-98, Grünthal, 1998). The approach makes use of classical probability theory and of the fuzzy-set theory. For each building type, three vulnerability indices need to be provided in order to follow an intensity-based macroseismic damage assessment approach: vulnerability (V), ductility (Q) and the t parameter. V is a measure of the ability of a building/building class to resist lateral seismic loading. The higher is the value of V, the lower the building resistance. Possible amplification effects due to different soil conditions are accounted for inside the vulnerability parameter. Q describes the rate of increase in the damage with earthquake demand level. The distribution of building damage is represented using beta distribution. The shape of the distribution is controlled by the t parameter where increasing t decreases the scatter as shown in Figure 5:

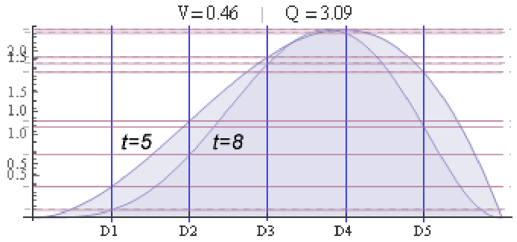

Figure 5. Effect of the *t* parameter on the shape of the beta distribution and the discrete damage classes. Vulnerability, ductility and intensity are kept constant. The EMS-98 five-damage grade discrete scale (from slight damage D1 to collapse D5) are represented on X-axis. The macroseismic intensity is represented on the Y-axis.

The association of the building types between PAGER, European (RISK-UE) and EMS98 classifications and the corresponding mean vulnerability (*V*) and ductility (*Q*) indices are given in Annex 1.

2.1.4 BUILDING DAMAGE

Building damage estimation is obtained from the normally distributed cumulative damage probability for each building type as function of *V*, *Q* and *t* (Lagomarsino and Giovinazzi, 2006). The analytical expression for the relationship between the mean damage grade, μ_D (mean of the discrete beta distribution) – intensity (*I*) and vulnerability index, *V* (Equation 1), allows estimation of the building damage distribution once vulnerability index *V* is known (Figure 6a). The cumulative damage probability is discretized to obtain the five damage states (Figure 6b):

- D1: Slight Damage
- D2: Moderate Damage
- D3: Substantial to Heavy Damage
- D4: Very Heavy Damage
- D5: Destruction

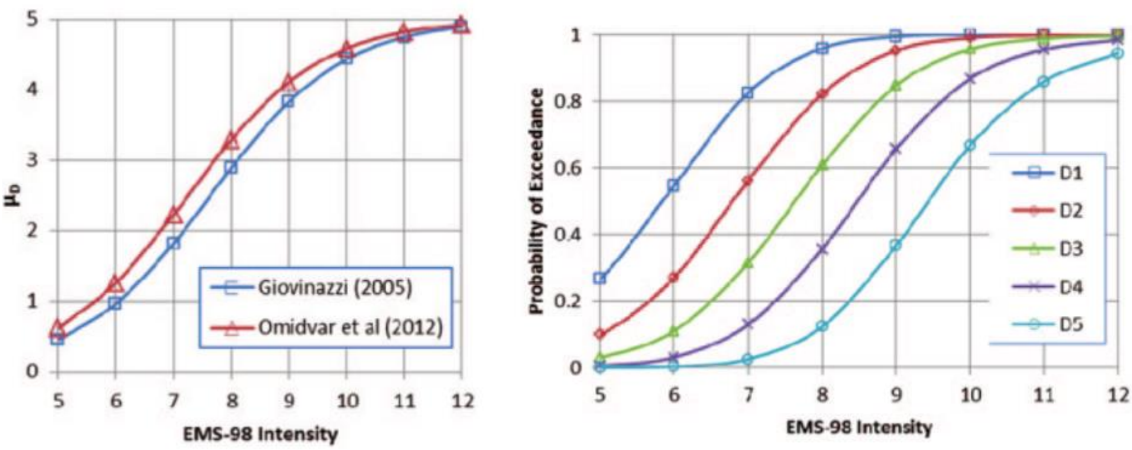

Figure 6. a)Vulnerability curves for adobe buildings in Europe b) Fragility curves for adobe buildings in Europe (Costa et al., 2014)

$$\mu_{D=2.5}\left[1+tanh\left(\frac{I+6.25\,V-13.1}{Q}\right)\right]$$ **Equation 1**

The mean damage grade values (Equation 1) are then connected to the two parameters *r* and *t* (Equations 2 and 3) describing the continuous beta distribution with a 3rd degree polynomial of the form shown below (Equation 3). In the study of Giovinazzi and Lagomarsino (2005) based on empirical data, *t* values were assigned to different building types

$$(r = \quad t(0.007\mu_D^3 - 0.00525\,\mu_D^2 + 0.2875\mu_D$$ **Equation 3**

Table 2. Values of the t parameter for distributions including the uncertainly in the hazard description (Giovinazzi and Lagomarsino, 2005). Risk-UE building typology (adopted from Grünthal, 1998) is used in this table.

Building type	*t* parameter
M1 (Rubble stone) M2 (Adobe) M3 (Simple stone)	6
M4 (Massive stone) M5 (Unreinforced masonry, old bricks) M6 (Unreinforced masonry) M7 (Reinforced confined masonry) RC4 RC5 RC6	5
RC1 (Concrete moment frames) RC2 (Concrete shear walls) RC3 (Dual system) S (Steel moment frames) W (Wood structures)	4.5

). The only unknown parameter required to describe the damage distribution is *r*.

$$pdf_{(x)} = = \frac{\Gamma(t)}{\Gamma(r)\Gamma(t-r)} \frac{x^{r-1}(6-x)^{t-r-1}}{6^{t-1}}$$ **Equation 2**

Where Γis the gamma function and

$$r = t(0.007\mu_D^3 - 0.00525\,\mu_D^2 + 0.2875\mu_D$$ **Equation 3**

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RC1 (Concrete moment frames) RC2 (Concrete shear walls) RC3 (Dual system) S (Steel moment frames) W (Wood structures)	4.5

2.1.5 CASUALTIES

Human losses are estimated using analytical methods that consider building damage as the root cause for injuries and fatalities. The assessment of human losses requires the knowledge of building occupancy and the probability of a certain casualty rate by each damage state. The lack of information on casualty data makes it difficult to derive empirical relations between building damage states. In ELER three different approaches for casualty assessment are proposed: BU-KOERI (2003), Coburn and Spence (2002) and Risk-EU based on the findings of Bramerini et al., (1995).

The BU-KOERI (2003) method which relies on casualty data in urbanized areas from Turkish earthquakes (i.e. 1992 Erzincan earthquake, 1999 Kocaeli earthquake) assumes that the number of fatalities will be equal to the number of buildings in D4 and D5 damage states.

The models proposed by Coburn and Spence (2002) and Bramerini et al., (1995) evaluate the consequences of building damage on people only with respect to collapsed buildings (building damage = D5). The correlations proposed in these two models refer to building damage and provide the results in terms of four severity levels:

- S1 Light injury non necessitating hospitalization
- S2 Injury requiring hospital treatment
- S3 Severely injured
- S4 Death

For this study, the casualty vulnerability relationships used in the Risk-UE project and based on the findings of Bramerini et al., (1995) are used. The model computes together the percentage of dead S4 and severely injured S3 (**Error! Reference source not found.**).

$$P_{S3+S4} = 0.3P_5 \qquad \textbf{Equation 4}$$

where P5 the probability associated with damage grade D5.

The study of Bramerini et al., (1995) resulted in the following correlations between damage grades and effects of these on population (Table 3):

Table 3. Correlation between damage grades and their effects on the built environment and population

Effects to people and impact on the built environment		
BUILDINGS	Unusuable	40% of buildings with damage grade 3 and 100% of buildings with damage grades 4 and 5
	Collapsed	Buildings with damage grade 5
PEOPLE	Homeless	100% of the population living in unusable buildings – casualties and severely injured
	Casualties and severely injured	30% of the population living in collapsed buildings

2.1.6 ECONOMIC LOSS

Economic loss refers here to the conversion of physical damage into monetary value using local estimates of repair and reconstruction costs. In ELER, direct economic losses corresponding to the losses caused by damage to the built-up environment can be estimated. Losses due to damage buildings are usually expressed in terms of "Mean Damage Ratio" (MDR) defined as the cost of repairing the structure divided by replacement cost:

$$MDR = \frac{reconstruction\ cost}{replacement\ value} \qquad 0 < MDR < 1 \qquad \textbf{Equation 5}$$

Different correlations (loss functions) between the damage grades and the MDR are proposed in the literature, obtained though processing the data from past significant earthquakes. The economic loss module developed in ELER v3.0 relies on user-defined loss ratios for the EMS98 damage states (D1 to D5).The MDRs are used to convert the number of damaged buildings in each grid to cell based MDR values. ELER computes the monetary value of direct economic losses by multiplying the MDR by the total building cost for each building type of the building inventory. This is expressed with the following equation:

Economic Loss (building type, D_k*)= MDR (*D_k*) x Building Cost (building type)* **Equation 6**

Where the MDR is a function of the building damage state D_k and the building cost is defined for each building type in the building database.
For this study, the default MDR values proposed by BU-KOERI (2003) for each damage state are used. Table 4 gives examples of different MDR values found in the literature and in risk assessment models.

Table 4. MDR values for loss estimations

D_k	BU-KOERI (2003)	Hazus (1999)	Bramerini et al., (1995)	ATC 13 (1987)	Tyagunov et al., (2006)
D1	0.05	0.02	0.01	0.05	0.05
D2	0.2	0.1	0.1	0.2	0.1
D3	0.5	0.5	0.35	0.55	0.4
D4	0.8	1	0.75	0.9	0.8
D5	1	1	1	1	1

2.2 APPLICATION OF ELER FOR RISK ASSESSMENT AT THE EU LEVEL

Obtaining reliable input data that meet the requirements of the risk modelling framework represents the most difficult and time-consuming part of the seismic risk assessment. This is particularly true when preprocessing is required to obtain the data in some standard and uniform format to be input into the selected risk modelling platform. This section discusses the main data that were collected, processed and used for assessing seismic risk at EU level according to level 1 analysis of ELER.

2.2.1 INTENSITY BASED HAZARD DATA

As previously mentioned the European probabilistic seismic hazard data produced in the context of the SHARE project was used in this study (Woessner et al., 2015). The results are available in the form of exceedance probabilities of ground motion measures within a specific return period (data for five different return periods and in terms of spectral acceleration for at least twelve periods of vibration are available for download from the European Facility for Earthquake Hazard & Risk[10]).

For the purpose of this feasibility study, data corresponding to 10% exceedance probability in 50 years (i.e. equivalent to an average recurrence of such ground motions every 475-year) was used for evaluating the potentials of performing a probabilistic seismic risk assessment (Figure 3). This return period is usually considered for the maximum credible earthquake (Woo, 2002) and is prescribed by the national building codes in Europe for standard buildings.

The pan-European hazard data produced in the context of SHARE project is represented through map of PGA and SA. The unit is "g" standing for gravitational acceleration. However, for level 1 analysis in ELER, hazard data in the form of instrumental intensity distribution is necessary for the building damage estimations. Hence, it was necessary to convert the hazard data from PGA into the Modified Mercalli Intensity scale (MMI).

The intensity values can be derived from PGA values using a correlation relationship. Focusing either on regional or worldwide data, many empirical relations have been proposed to relate the macroseismic intensity (MMI) to PGA (Murphy, 1978; Trifunac and Brady, 1976; Wald et al., 1999). The variety of relationships between MMI and PGA and the inherent statistical variability in predicting MMI make it difficult to identify a single relationship to be applied uniformly across EU countries.

Regions with high seismicity (e.g. Greece, Italy) are usually characterized by a better understanding of historical seismicity and are subject to detailed studies for correlating ground motion parameters to macroseismic intensities either at regional or national levels.

For these three high seismicity regions, it was decided to use state-of-the art, nationally derived empirical relationships. The general MMI-PGA relationships is expressed as follows:

$$MMI_{(Y)} = b_{0+} b_1 \overline{\log(Y)} \qquad \textbf{Equation 7}$$

where Y is the average of the ground motion parameter; b_0 the intercept and b_1 the slope obtained from the linear regression.

The following values for the intercept and slope were applied respectively:

- For Greece (Tselentis and Danciu, 2008): b_0 = - 0.946 ; b_1 = 3.563
- For Italy (Faenza and Michelini, 2010): b_0 = 1.68 ; b_1 = 2.58

[10] http://www.efehr.org:8080/jetspeed/portal/

For the rest of Europe the classical empirical relation by Wald et al. (1999), which is also implemented in the Earthquake Hazard Assessment (EHA) module of ELER, has been used, with: b_0 = - 1.66; b_1 = 3.66.

2.2.2 BUILDING INVENTORY FOR EU-28 COUNTRIES

The compilation of a consistent building inventory for 28 EU countries is a key point in the seismic risk assessment. The quality of the available building inventory, both in terms of structural and occupational parameters will determine the quality of the resulting loss estimation (BU-KOERI, 2010). A basic but comprehensive European database, was available for all EU countries with the expectation of Croatia, and provided within ELER as the default data of Level 1 analysis. The countrywide approximated building database was obtained from Corine Land Cover and population databases. It is provided in 150 sec arc grids for 27 countries in Europe for which the Corine Land Cover data are available. The methodology used in obtaining the country basis geographic distribution of the number of buildings from Corine Land Cover and Population databases is covered in Appendix A of ELER manual (BU-KOERI, 2010). Once the grid distributions of the total number of buildings were obtained, the approximate number of buildings in each building class (as defined in the European building classification system) were computed using the countrywide overall building class ratios provided in PAGER database (Jaiswal and Wald, 2008). The PAGER project provides the percentages of different construction types in all countries of the world for both urban and rural settlements and residential and non-residential occupancy types, making use of a HAZUS99 type classification. Corresponding European Building Taxonomy classes (Risk-UE) have been identified for the structural types of the PAGER classification system. Then these percentages have been used to convert the approximated grid based number of buildings to an inventory of different structural types in each county.

A slightly different approach was used for deriving the building stock and population distribution in 150 sec arc grids for Croatia. The step-wise approach includes:

1) An estimation of the total number of buildings in each cell

   The open-access global exposure data of GAR[11] (UNISDR, 2015) was used for deriving population data. The exposure data used for the GAR integrates population and country-specific building typology, use and value (De Bono and Chatenoux, 2015). It is represented as a group of buildings in each cell with a resolution of 5 x 5 km (approximately in the equator) Unfortunately, the GAR data does not include the total number of buildings by building type. The geographical distribution of the population corresponds to the coverage offered by LandScan with a 1 km resolution (Dobson et al., 2000). The average occupancy value of 5.1 persons per housing unit for Croatia was derived from the United Nations data (UNECE, (2006)). Using the total number of people in each cell and the average occupancy value, it is then possible to approximate the total number of buildings per cell.

2) An estimation of the number building per cell

[11] http://www.preventionweb.net/english/hyogo/gar/2015/en/home/data.php?iso=NLD

3) Once the total number of buildings is obtained for each cell, the fractions of different construction types in Croatia derived from PAGER database allows the disaggregation of the total number of buildings (*TB*) into different building types:

Once the total number of buildings is obtained for each cell, the fractions of different construction types in Croatia derived from PAGER database allows the disaggregation of the total number of buildings (*TB*) into different building types:

$$Total\ Bldg_{Croatia} = 0.15\ (W)*TB + 0.57\ (M5M)*TB + 0.22\ (M7)*TB + 0.06\ (RC2DCLIIM)*TB$$ **Equation 8**

With *W* = 0.15; *M5M*= 0.57; *M7*= 0.22; *RC2DCLIIM*= 0.06 (Jaiswal and Wald, 2008).
(For the description of building types, see Annex 1).

2.2.3 ESTIMATION OF BUILDINGS COSTS

For the assessment of economic losses, in particular the PML (for 475-year return period), information on building costs needs to be assigned to each building type of the European building inventory. In this study, the assessment of economic losses is based on the assumption that residential buildings are dominant in the building stock and that the damage affecting these buildings is an indicator of the total direct economic impact. A more complete assessment should consider other components of the physical environment such as commercial, industrial buildings and infrastructure (e.g. transport infrastructure). The default European building inventory provided in ELER does not include information on building replacement value. Collecting information about the monetary value of exposed buildings for all 28 countries is unrealistic despite the availability of data at municipal level in some EU countries (e.g. the uniform database on the reconstruction costs of residential buildings in Germany as estimated by Kleist et al., (2006)).

To circumvent the challenge of obtaining a valuation of exposed buildings with a pure bottom-up approach, a top-down or "downscaling" approach was developed in the context of the GAR 2015. Simply presented, the approach relies on national indicators (i.e. socio-economic data, building types and capital stock) successively disaggregated onto 5x5 km grid and used as proxies to estimate the population distribution, building structure typology, ownership (private/public), use sector (e.g. residential, health, education) and the building value. In order to establish the monetary value of exposed assets the World Bank 2011 data on capital stock per country was used. The capital stock was downscaled from the national/sub-national level to the cell level using LandScan population data of 2011 at a resolution of 30". Details on the methodology used for estimating the value of exposed assets can be found in De Bono and Chatenoux (2015).
Despite many assumptions, the global exposure data for the GAR 2015 has several advantages:

i) it is the only open database including the value of exposed assets that covers all EU-28 countries,
ii) it ensures a good uniformity allowing the comparison of the results across the different countries,
iii) the format and the resolution (5x5 km) are compatible with the European building database provided in ELER.

Consequently, the global exposure data was used for deriving the replacement value of the different building types within each of the 28 EU countries.

The average costs for each building type of the European building database were calculated at the country level from the global exposure data. The following graph (**Error! Reference source not found.**) represents the average costs of the building types in Italy (following PAGER taxonomy). It shows a high variability in the values of buildings measured by the standard deviation (σ). While the global exposure data takes into account explicitly the spatial variations of the values of exposed assets, ELER allows the assignment of a unique value per building type without consideration of the local variations of property costs. Due to the high variability of building costs observed in most of the countries, it was decided to use the median value instead of the mean as a replacement cost for each building type.

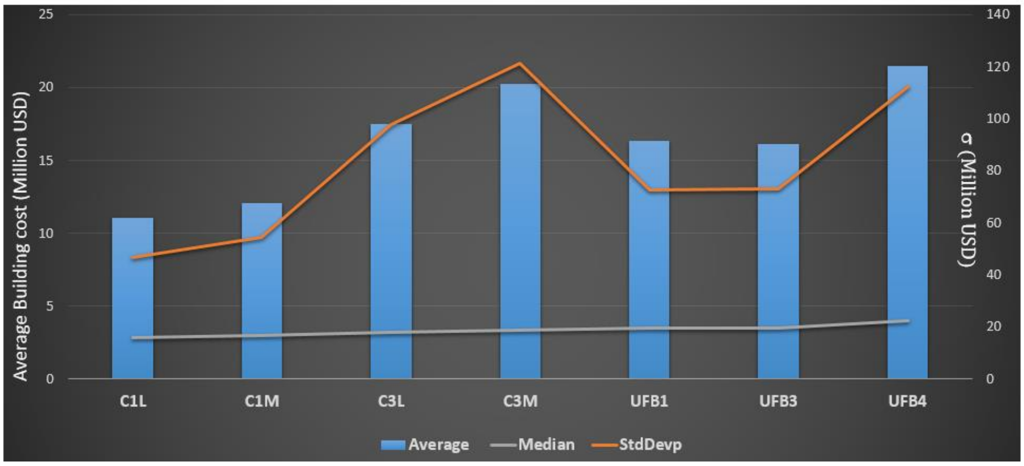


Figure 7. Average and median building costs (in Million USD) in Italy derived from the global exposure data of the GAR 2015

3 RESULTS FOR EARTHQUAKE HAZARD WITH A 475-YEAR RETURN PERIOD

The results of the pan-European probabilistic risk assessment are expressed as expected casualties and PML for the earthquake hazard with a 475-year return period. The variety of uncertainties originating from different sources and present at every step of the risk assessment are addressed in the sensitivity analysis with the purpose of shedding light on the influence of methodological and data input choices on the risk estimates.

3.1 EXPECTED CASUALTIES

Casualties in ELER level 1 analysis are calculated based on building damage and at four severity levels: S1 Light injury; S2 Injury requiring hospital treatment; S3 Severely injured and S4 Death. For this study, both severity levels S3 and S4 (referred to here by casualties), related to building damage state D5 are considered. Figure 8 shows the distribution of casualties (S3+S4) in the four EU countries with the highest levels of seismic risk: 6665 in Italy (Figure 8 a), 6456 in Cyprus (Figure 8 b), 2825 in Romania (Figure 8 c) and 2709 in Greece (Figure 8 d).

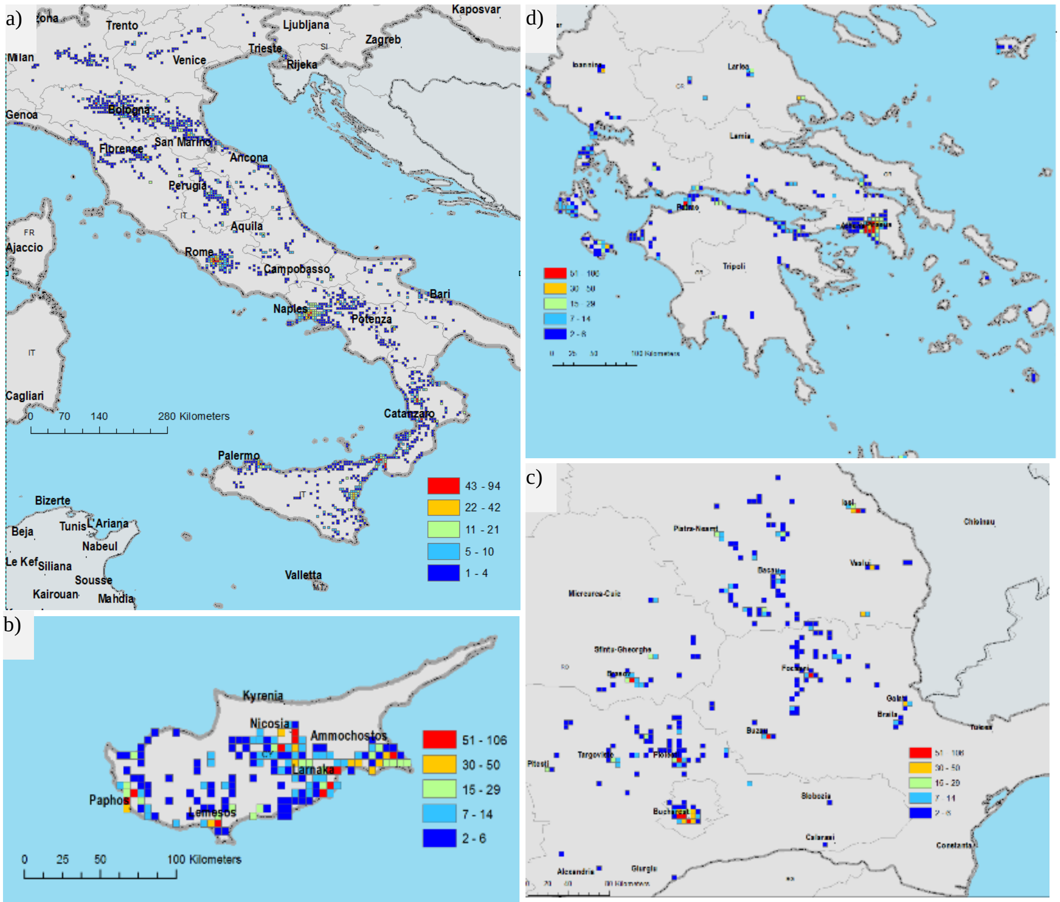


Figure 8. Spatial distribution of casualties in Italy (a), Cyprus (b), Romania (c) and Greece (d).

The results presented here correspond to a daytime population. They tend to show a concentration of casualties in the major urbanized areas (e.g. Naples, Bucharest, and Athens). A better understanding of casualties' distribution within each country requires an analysis of casualty rates by building type to identify the most vulnerable buildings. This issue will be addressed in a follow-up study.

3.2 PROBABLE MAXIMUM LOSSES

The economic loss was calculated within each cell of the gridded European building database. It was then aggregated at city, NUTS 2 and national levels. Aggregation of the results at the regional and national levels is meant to provide an overview of loss estimates for an eventual comparison with the results of other studies (e.g. the PML for 475- year return period calculated as part of the GAR 2015). The aggregated results are not to be used for comparison between the countries nor have any value within a decision-making context.

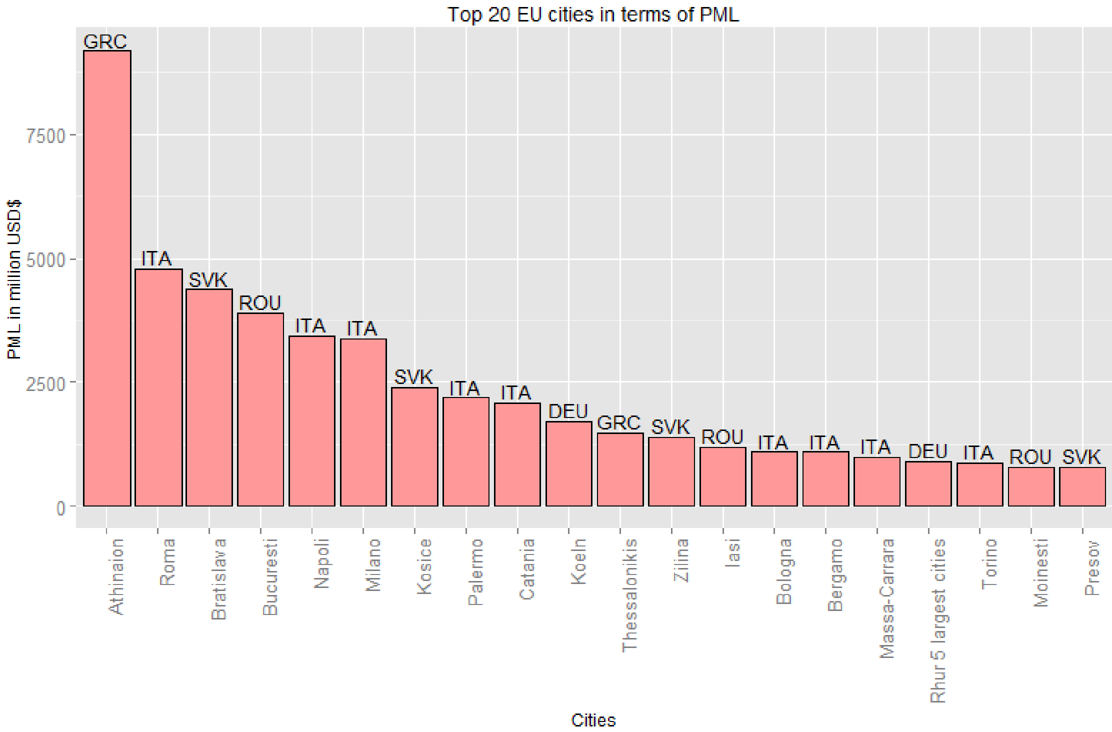
3.2.1 AGGREGATION AT CITY LEVEL

Several definitions exist for the concept of urban areas and different references are available for the delineation of cities in Europe. Urban Morphological Zones[12] (UMZ) used by the European Environment Agency (EEA) were used as a reference for delimiting the extent of EU cities. Those urban areas are defined from land cover classes contributing to the urban tissue and function. UMZ were defined from Corine Land Cover, which is also the basis for the exposure database used in our analysis. They refer to built-up areas without consideration of the population distribution, making them suitable for our analysis in comparison to other definitions that consider functional economic links, community flows and population distribution. They are formally defined as formally defined as built-up areas lying less than 200 m apart.

Economic losses were assessed for EU cities defined according to the UMZ. The results in Figure 9 illustrate the top 20 EU cities with the highest expected economic losses expressed in absolute and relative to regional GDP (GDP in 2013 at NUTS2[13]) values. Given the distribution of the seismic hazard (Figure 3), the cities most at risk are located in areas where large earthquakes and significant damage were recorded. Torino with a moderate seismic hazard is not expected to rank in the top 20 EU cities with high seismic risk. The spatial delineation of cities according to the UMZ concept and the conversion from vector to raster format introduces an error in the "urban footprint" and subsequently in the aggregated economic losses. Using a different delineation of EU cities is likely to produce a different ranking of cities. Out of the 20 cities, 9 are located in Italy, 4 in Slovakia, 3 in Romania, 2 in Greece and 2 in Germany (for the latter, the UMZ covers 5 spatially contiguous cities).

[12] http://www.eea.europa.eu/data-and-maps/data/urban-morphological-zones-2006

[13] http://ec.europa.eu/eurostat/statistics-explained/index.php/GDP_at_regional_level



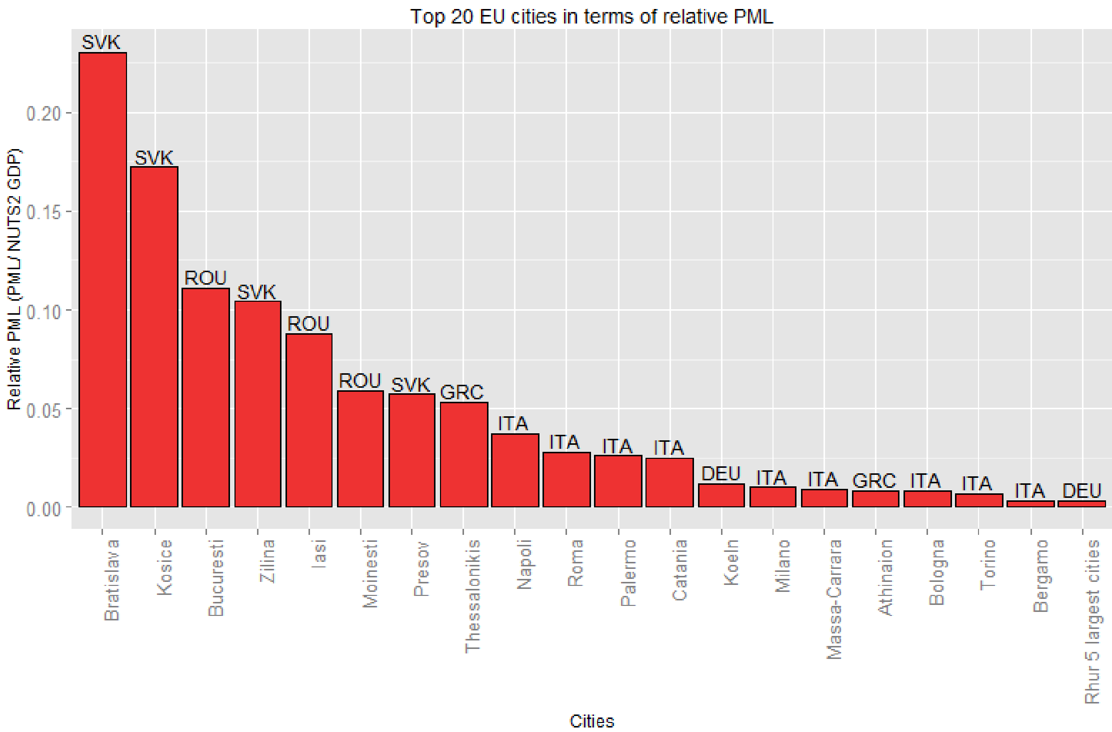


Figure 9. Top 20 EU cities in terms of expected economic losses expressed in absolute (a) and relative to NUTS 2 GDP (b) values.

3.2.2 AGGREGATION AT REGIONAL LEVEL

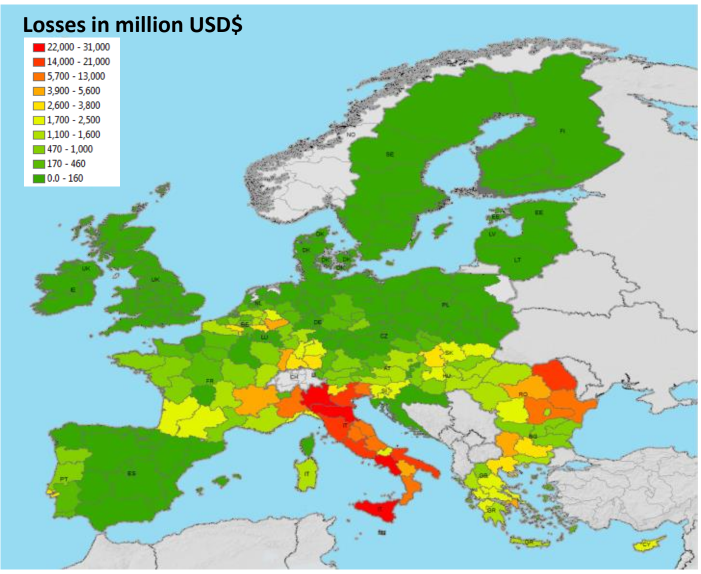


Figure 10. Distribution of estimated economic losses aggregated at NUTS2 level.

The aggregated PML at NUTS 2 (Figure 10) show high economic loss estimates in almost all of the 20 Italian regions, with the exception of Sardinia. North-eastern regions of Romania also show moderate to high economic losses. Some regions in Greece, France, Bulgaria and Germany show moderate economic loss. These results are consistent with National Risk Assessment reports in which the same countries identified seismic hazard and their socio-economic impacts as a big concern, with the exception of the Czech Republic, where the modelled seismic risk seems to be relatively low (see section 1.4).

The spatial distribution of the economic loss can be better captured bylooking at the spatial distribution of building damage. As an example, the non-aggregated building damage for damage states D4 and D5 is illustrated in Figure 11-a for the Italian territory. The map of building damage exhibits strong correlation with the macro-seismic intensity map derived from ground motion map of SHARE project (Figure 11-b). The similarities between the patterns of building damage and seismic hazard map indicate the dependence of the risk on ground motion intensity.

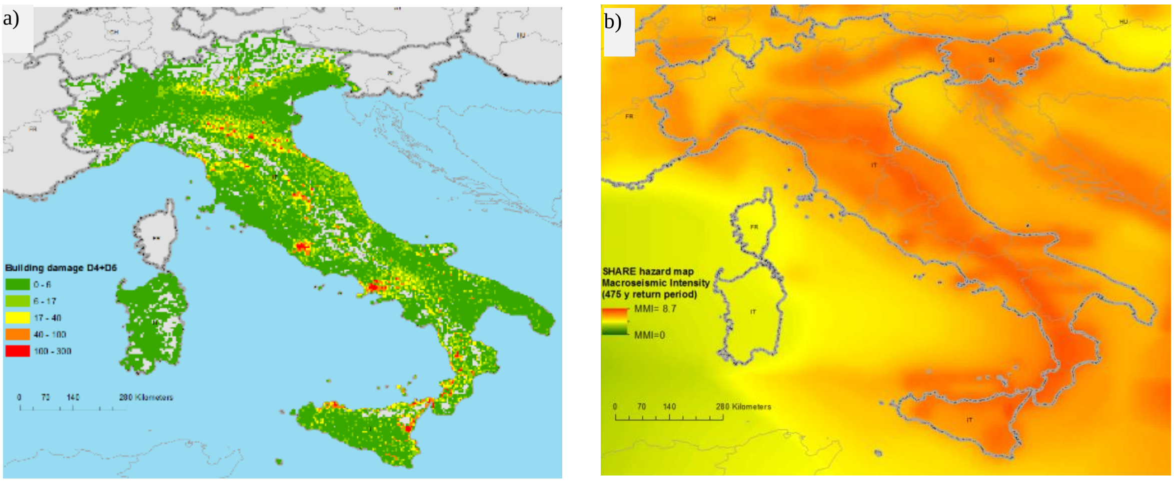


Figure 11. Spatial distribution of building damage in Italy (a) and seismic hazard map for the 475 year return period (b)

3.2.3 Aggregation at national level

For the purpose of comparison with the risk outputs of GAR 2015, the PML estimates were aggregated at the national level. The results of the two probabilistic risk assessments are shown in Figure 12. The PML values shown for the GAR 2015 refer to the economic loss estimates associated with the return period of 475-year of the seismic hazard.

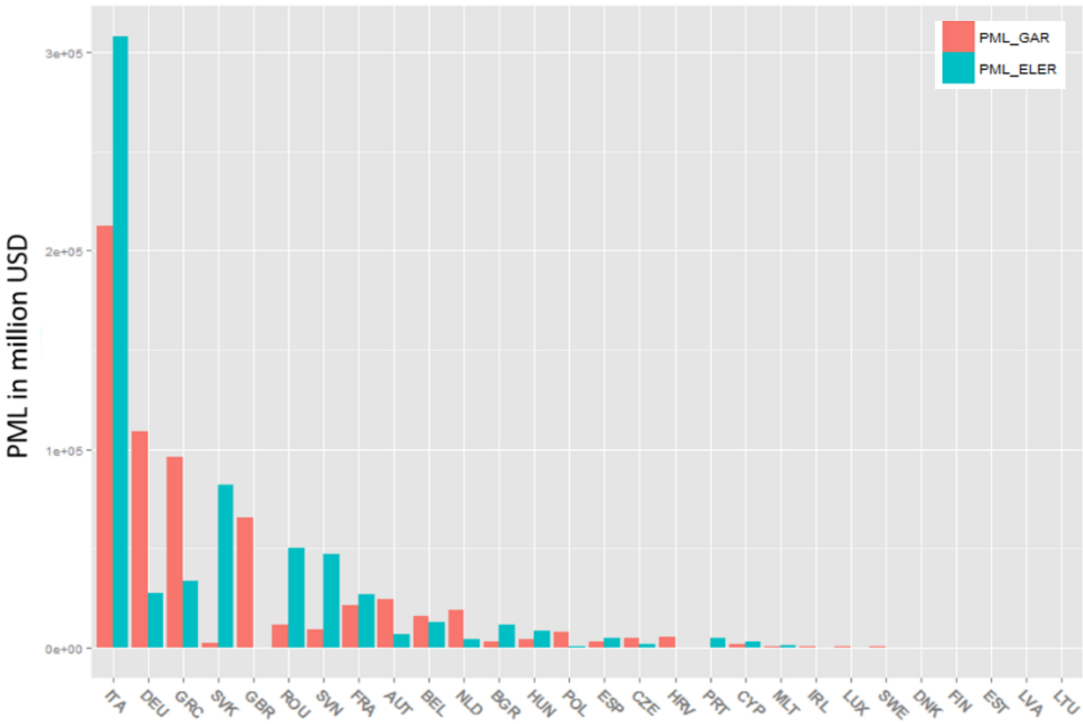


Figure 12. PML values obtained with ELER (blue) and in the context of GAR 2015 (red). The results correspond to economic loss estimates associated with the return period of 475 years of the seismic hazard

The comparison of the risk assessment results of the current study with those obtained in the context of the GAR 2015 using CAPRA GIS show large unsystematic discrepancies. Risk assessment with ELER gave much higher estimates of economic losses in Italy, Slovakia, Romania and Slovenia. Whereas for Germany, Greece, Great Britain, Austria and Netherlands, the GAR 2015 estimates were higher than those obtained with ELER.

The differences in the estimates can be explained by differences in both i) the risk assessment models and 2) the input data used in these models including hazard data, the exposure database and the vulnerability functions. In addition, it is useful to remind that given the global scope of GAR 2015, a coarse-grain analysis approach for both hazard and risk assessments has been implemented.

Another major factor influencing the variability of the economic loss estimates is the difference in the approaches used in CAPRA GIS and in ELER for assigning costs to the exposed assets. While the exposure data in CAPRA GIS takes into account explicitly the spatial variations of the values of exposed assets, ELER allows the assignment of a unique value per building type without consideration of the local variations of property costs. This limitation of ELER may lead to unrealistic economic loss estimates especially in large cities with high property and building costs.

The next section, which deals with sensitivity analysis, may give more insights into the sources of variability in the risk assessment and consequently help understanding the reasons behind the differences in the PML estimates of the GAR 2015 and the current study.

3.3 Sensitivity analysis

The methodological and input data choices inevitably introduce uncertainty in the results of the seismic risk assessment. A variety of uncertainties and errors originating from different sources are present at every step of the risk assessment process (e.g. natural variability of the phenomena under investigation, incompleteness of input data or inadequacies in the models and methods). Many assumptions had to be made in order to complete the pan-European risk analysis. The impact of each of these assumptions on the results can be assessed through a sensitivity analysis. It is beyond the scope of this study to analyse all sources of uncertainty, especially those related to the risk assessment model, which were already discussed in several publications (BU-KOERI, 2010; Erdik et al., 2010; Hancilar et al., 2010).

The emphasis in the current study is placed on the analysis of epistemic uncertainties, which are related to the variability of the input variables including the sensitivity analysis of the resulting seismic risk assessments with regard to the different input datasets: hazard and exposure data. A more comprehensive sensitivity analysis would have to consider the uncertainties associated with selection of MDR functions, i.e. the relationships between the damage state of affected buildings (described by the structural damage grade) and the corresponding level of direct losses (Tyagunov et al., 2013) (see section 2.1.6 on the variability of MDR values).

3.3.1 Sensitivity to hazard data

Sensitivity analysis to hazard data was investigated through a) an investigation of the influence of MMI-PGA relationships for the conversion of ground motion data to macroseismic intensities and b) an analysis of the influence of the input probabilistic hazard map.

a) Influence of MMI-PGA relationships

In section 2.2.1, the different intensity MMI-PGA relationships selected for the conversion of PGA values to intensity values were presented. The choice of the intercept b_0 and slope b_1 was driven by the existing regional or national studies that attempted to derive empirical relationships using observed data. To examine the influence of the choices made when selecting these parameters, a small area (circa 334 x 556 km) around the city of Ioannina in Greece was defined for the analysis. The parameters proposed by Faenza and Michelini (2010) (b_0 = 1.68; b_1 = 2.58) and by Tselentis and Danciu (2008) (b_0 = - 0.946; b_1 = 3.563) were applied.
Figure 13 shows the distribution of the buildings in damage states D4 and D5 obtained with the two different seismic hazard datasets. The comparison of the results in terms of total building damage D4+D5 (4021 versus 3570) shows a percentage difference of 12%. The parameters proposed by Tselentis and Danciu (2008) for Greece lead to more conservative estimates of the building damage.

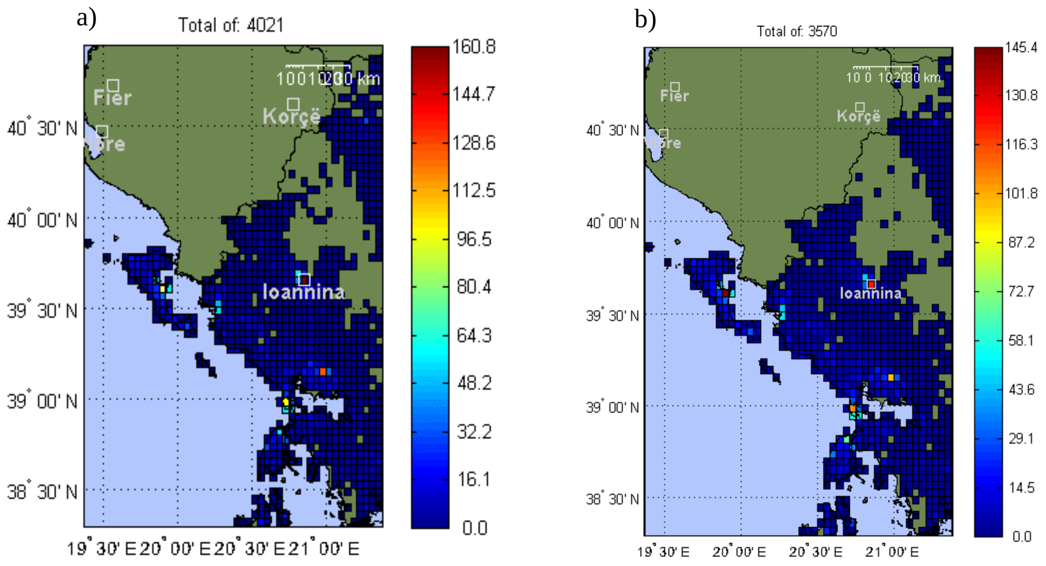


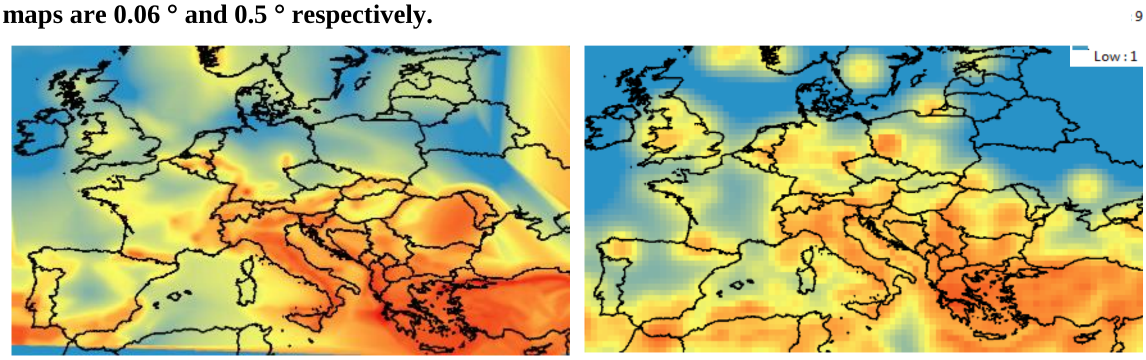
Figure 13. Distribution of total building damage (D4+D5) a) with b_0 = 1.68; b_1 = 2.58 (Faenza and Michelini, 2010) and b) *b0* = -0.946; *b1* = 3.563 (Tselentic and Danciu 2008).

b) Influence of the input probabilistic hazard map

Several studies addressing uncertainty in seismic risk assessment (Bazzurro and Luco, 2005; Tyagunov et al., 2013) found that the greatest contribution to the total uncertainty comes from the hazard part (mainly from the selected intensity prediction equations). Besides the resolution of the seismic hazard map may also strongly influence the risk assessment results. In order to study the contribution of the hazard component to the risk assessment results, the probabilistic seismic hazard assessment (PSHA) at global level developed as part of the GAR 2015 was tested in

ELER. For a consistent comparison with the risk assessment using SHARE hazard data, the global hazard map for peak ground acceleration (PGA) and 475-year return period was used in this test. Both datasets were converted to intensity values using the MMI-PGA relationship developed by Wald (1999). The resulting seismic hazard maps represented using the same macroseismic intensity scale are shown in Figure 14.

Figure 14. Probabilistic seismic hazard maps obtained from SHARE project (a) and GAR 2015 (b) represented in MMI scale for the 475 years return period. The spatial resolutions of the hazard maps are 0.06 ° and 0.5 ° respectively.



The Marmara region in Turkey, for which a detailed building inventory is available as a sample data in ELER, was selected for the test. The grid based building inventory of Marmara region is based on the year 2000 building census tracts carried out by Turkish Statistical Institute. The data include, the occupational type, the construction type and the number of floors of each building. The construction type and number of floors are the main parameters affecting the earthquake performance of buildings. The inventory is classified in accordance with the EMS building classification system.

The results of the comparative risk analysis in terms of building damage, economic losses and casualties are shown in Table 5. The results obtained with the two different hazard maps are significantly different (the percentage differences[14] are 171%, 112% and 186% for building damage, economic loss and casualties, respectively). They suggest that the use of hazard data intended for global applications, within a seismic risk analysis at regional level, may introduce a considerable (and possibly excessive) uncertainty in the final results. The global seismic hazard map of the GAR 2015, initially intended for global applications should be treated carefully especially in regions of moderate to high seismicity. The authors of the global seismic hazard map acknowledge its limitations, including the non-consideration of localized faults or conditions that could represent an increased seismic hazard (CIMNE-INGENIAR, 2015).

[14] The percentage difference is calculated as the difference between two values divided by the average of the two values shown as a percentage.

Table 5. Results of seismic risk assessment in Marmara region obtained with SHARE and GAR 2015 hazard maps

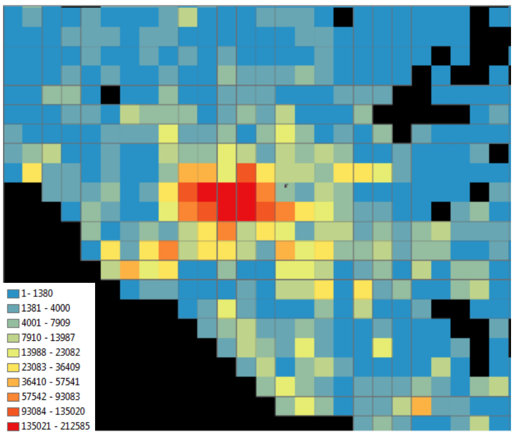
	SHARE hazard data	GAR 2015 hazard data
Building damage D4+ D5	79690	6 759
Economic loss (in Million USD)	289 234	81 323
Casualties S3 + S4	129958	4 720

3.3.2 SENSITIVITY TO POPULATION DATA

The default grid based population data integrated in the European building database was used in the seismic risk assessment for estimating casualties. The population data for the 28 EU countries was derived from LandScan population data (Dobson et al., 2000). LandScan global population data has an approximate resolution of 1x1 km^2 resolution at the equator (30 sec arc grids) and represents ‘ambient population’. The data was aggregated to 150 sec arc grids to match the building database. Recently, new population grids were produced for selected countries in Europe, at 10, 100, and 1000 m resolutions (Freire and Halkia, 2014); Freire et al., 2015). These grids were generated by disaggregating residential population from the 2011 round of censuses to built-up areas as mapped in the European Settlement Model (ESM) layer (Ferri, 2014; Ferri et al., 2014) developed in the context of the Global Human Settlement Layer (GHSL) project (Pesaresi et al., 2013).

Differently from LandScan, which aims at representing ‘ambient population’, GHSL-based population grids represent residential-based population in buildings. The improved population data represents an interesting input dataset for the assessment of casualties. For the sensitivity analysis, population data for Italy was available at 100 m resolution. It was obtained by disaggregating 2011 census tract population (cezione) into the GHSL built-up layer informed by the Corine Land Cover Refined 2006 layer (Batista e Silva et al., 2013). The following figure shows the differences in the level of detail between the default grid based population data provided in ELER and the one obtained with the method of Freire et al. (2015).

LandScan population data (150 sec arc grids)



Population data derived from the GHSL (100 x 100m)

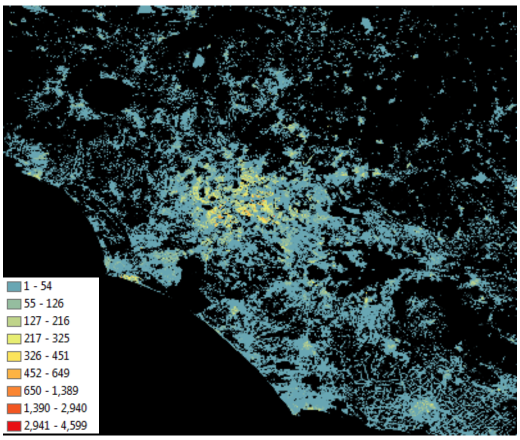


Figure 15. Gridded population data obtained from LandScan (left) and from the GHSL (right) shown for Rome, Italy.

The calculated casualty estimates (for severity levels S3 and S4) obtained by the use of the two population datasets for Italy gave the following total casualties (S3+S4):

- 6 665 with LandScan derived population data
- 10 399 with GHSL derived population data

The more detailed population data provides predictably higher casualty estimates. The large percentage difference of 44% in the results can be possibly attributed to:

- The difference in the resolution and accuracy of the demographic data, which can significantly affect the results of seismic risk assessment.
- The differences in the concepts between LandScan, which represents ambient population, and the population data derived from GHSL, which is based on built-up areas. Knowing that casualty estimates are directly derived from building damage (see section 2.1.5), it is then plausible to obtain higher casualties when exploiting the GHSL derived population data.

From this analysis, one may conclude that the results of the seismic risk assessment in ELER tend to show large variations related to differences between the default input population data and user defined data.

3.3.3 SENSITIVITY TO BUILDING COST

According to Tyagunov et al., (2013), the main uncertainties in exposure modelling are associated with the spatial distribution of the building stock, the building types and the assessment of their characteristics related to both vulnerability and costs. A comprehensive sensitivity analysis should consider the individual components of the exposure model. The aim of the sensitivity analysis performed in this study is to shed light on the main uncertainties related to methodological choices in data collection. Therefore, consideration is given here to the choice of the method for deriving building costs.

The assessment of the PML in ELER was based on building replacement values derived from the global exposure database used in GAR 2015. Modelling the value of exposed assets for GAR 2015 involved several assumptions and proxies described in De Bono and Chatenoux (2015). In addition to the uncertainty related to these assumptions, the choice made in the current study of using the median value building costs introduces another source of error. To analyse and quantify the influence of this choice on the PML, the economic losses in Slovenia were computed using both the median and average building costs derived from the global exposure database, while keeping all other parameters constant. Figure 16 shows the spatial distribution of the economic loss using the two estimates of building values. The comparison shows that despite the identical patterns of economic loss distribution, there is a percentage difference of 95% between the two estimates. Assigning a median building cost to each building type gave conservative results with a total of 0.46 Million USD compared to the use of the average building cost which resulted in large (and probably excessive) estimates with a total of 1.3 Million USD. These large differences highlight the criticality of the modelled exposure, in particular the estimation of exposed assets values in seismic risk assessment. They also pinpoint the shortcomings of assigning one economic value per building type independently of the spatial location.

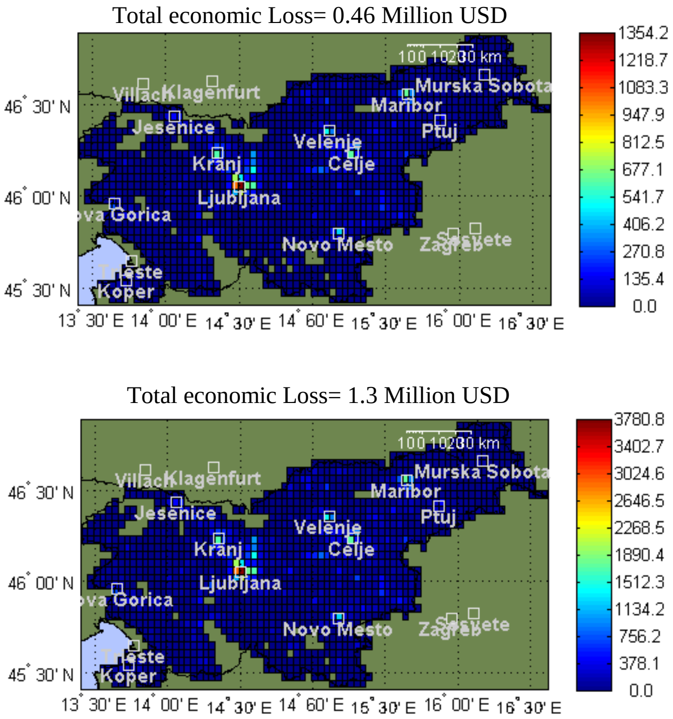


Figure 16. Total economic losses (in Million USD) in Slovenia obtained with estimates of the median (a) and average (b) building costs derived from the global exposure database of the GAR 2015.

4 SHORTCOMINGS AND FUTURE DIRECTIONS

The methods and results presented in this report should constitute a "proof of concept" which aim is to demonstrate the feasibility of performing a probabilistic seismic risk assessment at a pan-European level with reasonable effort. The experiments conducted in this study were successful in: i) pooling open-access data from different sources in a homogeneous format for all 28 EU countries, ii) assessing the applicability of models and the usability of datasets developed in the context of EU research projects (NERIES, Risk-UE and SHARE), iii) highlighting the main sources of uncertainties that need to be carefully considered when performing a seismic risk assessment, iv) and finally, demonstrating the potential of conducting a probabilistic seismic risk assessment at the EU level.

Although the risk estimates obtained in this study have limited value in a decision-making context or for inter-country comparisons, they can still be used for the following purposes:

- in benchmarking exercises to monitor changes in loss over time (in relation to changes in human and physical exposure and vulnerability),
- in drawing attention to the areas where necessary refinements are required and detailed seismic risk assessments are desirable,
- in complementing and regularly updating the cross-sector overview of disaster risks at Union level as stipulated in article 5 of the Union Civil Protection Mechanism (*Decision No 1313/2013/EU*),
- in stimulating efforts in the Member States to collect more detailed exposure data at local and regional levels for more refined risk assessments.

The shortcomings of the study carried out so far are related to both methodological and input data choices:

Shortcomings related to the risk modelling platform

- One of the limitations of ELER is the assignment of a unique value per building type without consideration of the local variations of property costs. This introducing an error in the calculated economic losses. One way to reduce this error is to consider the spatial variability of property costs. This can be implemented in a post-processing stage by applying region-dependent correction factors derived from maps of property costs.

- Level 1 seismic risk analysis of ELER is based on macroseismic intensities for modeling vulnerability and assessing damage. It is frequently argued that the use of macroseismic intensity leads to more reliable damage/loss estimates as it is possible to reduce the uncertainty in the empirical vulnerability model with macroseismic intensity data usually available following an event (Crowley, 2014). However, the need to convert ground-motion data to intensity values require a careful choice of the correlation tailored to area under analysis. A more accurate estimation of macroseismic intensity would need to consider separately high and low intensities: the former correlate fairly well with both PGA and PGV values while the latter correlate best with PGV values (Wald et al., 1999). Given the time constraints for this work, only the relationships between MMI and PGA were considered and applied for computing the macroseismic intensity based hazard maps.

- Unlike CAPRA GIS and OpenQuake, the risk assessment approach in ELER does not accommodate a fully probabilistic risk assessment where all possible and relevant deterministic earthquake scenarios are considered together with all possible ground motion probability levels. It is still however possible to perform a pseudo-probabilistic risk assessment by running the model with seismic hazard maps with different return periods (at least three e.g. 475, 975 and 4975-year return periods). Since the scope of the current work is to study the feasibility of performing a probabilistic risk assessment, rather than to perform a complete fully probabilistic analysis, it was decided to limit the case study to a scenario-based risk assessment associated to earthquake hazard with a 475-year return period.

Shortcomings related to the input data

- The exposure data used in the context of this experiment has several limitations related to the poor data available at the EU level and to large number of assumptions used for deriving the building stocks, the building typologies and their monetary values. In particular, the rough estimation of building costs from the global exposure database of GAR 2015 introduces large errors in the results. The assignment of uncertainty to exposure data, as well as of any correlations in the uncertainty, is certainly an area that would benefit from increased research attention (Crowley, 2014).

- The use of spatially constant vulnerability functions per building type introduces additional errors in the estimation of building damage and consequently in casualty and economic loss estimates. Regionally adjusted building vulnerabilities would allow obtaining more reliable evaluations of losses. This is can be achieved, when regional intensity based vulnerability curves or sufficient observed damage data are available, the average curve can be shifted to obtain a better approximation of the regional data (Giovinazzi and Lagomarsino, 2004). ELER software allows the incorporation of a regional vulnerability variability factor if such information is available.

There are number of areas that require improvements and further research in view of a fully probabilistic pan-European risk assessment. Some avenues for future investigations are suggested here.

1) Recently the GEM foundation released the OpenQuake engine comprising a set of calculators capable of computing human or economic losses by considering the probably of all possible events. With the availability of the OpenQuake platform, it would interesting to run the same experiment using the same input data and to compare the outputs of the two models.

2) In view of obtaining reliable results that can be useful to inform policy makers and to complement national risk assessments, the work performed here can be improved by making use of local datasets and national expert elicitations. The latter can be useful for estimating building vulnerability and costs especially in countries where both empirical data and analytical models are missing.

3) It is also necessary to compare the results of the current study with national seismic risk maps. In particular, various studies have looked at the seismic risk to the building stock and population at the national level in Italy. Many of the original seismic risk maps for Italy were based on single ground-motion parameters to define the seismic hazard such as peak ground acceleration or macroseismic intensity (Lucantoni et al., 2001) or on mechanics-based vulnerability assessment procedures (Crowley et al., 2009). The aim of these comparisons would be to open the discussion on the best way to produce nationally and regionally relevant seismic risk assessments making use of the most-up-to-date information in the fields of seismic hazard evaluation, vulnerability assessment and exposure modelling.

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6 ANNEX 1: EUROPEAN (RISK-UE), EMS98 AND PAGER BUILDING TAXONOMY MATRICES

European (RISK-UE)		**EMS98**	**PAGER**	**V**	**Q**
Type	Description	Type	Type		
M1	RUBBLE STONE	M1			
M1_M	Mid-Rise		(M or M1+M2) + RE + RS	0.87	2.3
M1_w_M	Mid-Rise, wood slabs		RS1+RS2+RS3	0.85	2.3
M1_v_M	Mid-Rise, masonry vaults		RS4	0.95	2.3
M2	ADOBE (EARTH BRICKS)	M2	A or A1+A2+A3+A4+A5	0.84	2.3
M3	SIMPLE STONE	M3	DS	0.74	2.3
M3_w_M	Mid-Rise, wood slabs		DS1+DS2+DS3+DS4	0.72	2.3
M4	MASSIVE STONE	M4			
M4_M	Mid-Rise		MS	0.62	2.3
M5	UNREINFORCED MASONRY (OLD BRICKS)	M5			
M5_M	Mid-Rise		(UFB or UFB1+UFB2) +UCB	0.72	2.3
M5_w_M	Mid-Rise, wood slabs		UFB3	0.70	2.3
M6	UNREINFORCED MASONRY (R.C. FLOORS)	M6			
M6_M_PC	Mid-Rise, Pre-Code		UFB4	0.65	2.3
M7	REINFORCED OR CONFINED MASONRY	M7	RM or RM1+RM2	0.45	2.6
M7_L	Low-Rise		RM1L+RM2L	0.37	2.6
M7_M	Mid-Rise		RM1M+RM2M	0.45	2.6
M7_H	High-Rise		RM2H	0.53	2.6
RC1	CONCRETE MOMENT FRAME	RC1			

RC1_L	Low-Rise		C4L	0.62	2.3
RC1_M	Mid-Rise		C or C4 or C4M	0.64	2.3
RC1_H	High-Rise		C4H	0.68	2.3
RC1_DCM_II_L	Low-Rise, Medium Ductility, Zone II		C1L	0.36	2.5
RC1_DCM_II_M	Mid-Rise, Medium Ductility, Zone II		C1 or C1M	0.38	2.8
RC1_DCM_II_H	High-Rise, Medium Ductility, Zone II		C1H	0.40	2.8
RC2	CONCRETE SHEAR WALLS	RC2			
RC2_DCL_II_L	Low-Rise, Low Ductility, Zone II		C2L	0.40	2.3
RC2_DCL_II_M	Mid-Rise, Low Ductility, Zone II		C2 or C2M	0.38	2.3
RC2_DCL_II_H	High-Rise, Low Ductility, Zone II		C2H	0.38	2.3
RC3	DUAL SYSTEM				
RC3_L	Low-Rise		C3L	0.57	2.3
RC3_M	Mid-Rise		C3 or C3M	0.59	2.3
RC3_H	High-Rise		C3H	0.63	2.3
RC3_DCL_II_L	Low-Rise, Low Ductility, Zone II		C5L	0.45	2.3
RC3_DCL_II_M	Mid-Rise, Low Ductility, Zone II		(C5 or C5M) +PC1+(PC2 or PC2L+PC2M+PC2H) +TU	0.43	2.3
RC3_DCL_II_H	High-Rise, Low Ductility, Zone II		C5H	0.43	2.3
S	Steel Moment Frames		All steel structures	0.324	2.3
W	Wood Structures		All wood structures	0.447	2.3

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