SERA
Seismology and Earthquake Engineering
Research Infrastructure Alliance for Europe

DELIVERABLE

D26.3 Methods for Developing European Commercial and Industrial Exposure Models and Update on Residential Model

Work package	WP26 (JRA4: Risk Modelling Framework for Europe)
Lead	EUCENTRE
Authors	Helen Crowley, EUCENTRE Venetia Despotaki, GEM Foundation Daniela Rodrigues, EUCENTRE Vitor Silva, GEM Foundation Dragos Toma-Danila, NIEP Evi Riga, AUTH Anna Karatzetzou, AUTH Stavroula Fotopoulou, AUITH + Exposure contributors
Reviewers	Management Board
Approval	Management Board
Status	Final
Dissemination level	Public
Delivery deadline	30.04.2019
Submission date	30.04.2019
Intranet path	DOCUMENTS/DELIVERABLES/SERA_D26.3_Exposure_Models_Non-res_Res

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730900.

Table of Contents

Summary

SERA Deliverable D26.2 covered the methodology being used to develop an exposure model of the residential building stock in Europe and provided a v0 exposure model (covering just residential buildings). This deliverable focuses on the extension of this model to commercial and industrial buildings, and also provides an update of the status of the methodology being used to model the residential exposure model. This deliverable therefore provides an overview of the complete methodology that has been implemented in the European Exposure Model v0.1 and the updates towards v1.0 that will be released in April 2020. The European exposure models provides the spatial distribution of the residential, commercial and industrial building count, population and replacement cost, characterized in terms of building classes (described following the GEM Building taxonomy, as described in Deliverable D26.1). The residential and non-residential exposure models have been derived based on the latest national housing censuses, socio-economic indicators (e.g. labour force, population and floor area per worker per economic sector), and mapping schemes (also referred to as inference rules) developed by the authors together with local experts. These exposure models are being developed as input to the European seismic risk model (Deliverable D26.7). The majority of this deliverable has been used to produce a manuscript that has been submitted to Earthquake Spectra (Crowley et al., 2019).

1 Introduction

1.1.1 Foreword

One of the objectives of the Horizon 2020 project SERA (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe) is to produce, by April 2020, a uniform European Seismic Risk Model (ESRM20) covering 46 European countries. The intention is then for the ESRM20 to be integrated within the Global Earthquake Model (GEM) Foundation's mosaic of risk models (Silva et al., 2019). As with all of GEM's risk models, the ESRM20 will be comprised of three main components: an exposure model defining the spatial distribution of the number of residential, industrial and commercial buildings, and their occupants and replacement cost, characterized in terms of building classes; a suite of fragility/vulnerability functions to estimate the likelihood of damage/loss of each building class, conditioned on a set of ground shaking intensity measure (IM) levels (described in Deliverable D26.5); and a probabilistic seismic hazard assessment (PSHA) model characterizing the probability of surface ground shaking in the region (e.g. ESHM13 model - Woessner et al. 2013 - and the ESHM20 update to this model that is currently being carried out within SERA work package JRA3).

In December 2018 GEM released a global seismic risk model (GEM 2018) that made use of version 0.1 of the European Exposure Model being developed as part of ESRM20. The features of this exposure model are described herein, as well as the updates that are currently being undertaken towards the development of v1.0 that will be used in the ESRM20. All development versions of the European Exposure Model are being made available on a European Seismic Risk Services platform (https://eu-risk.eucentre.it) in order to share the methods, models and data, and to obtain feedback from local experts across Europe, and thus continually improve the models.

1.1.2 Existing Exposure Modelling Efforts covering Europe

There have been a number of regional and global efforts to develop exposure models, all of which have provided important input to the current methodology that is being employed for the European exposure model. One of the first open and publicly available global building inventory databases was developed for rapid loss assessment within the PAGER system (Jaiswal and Wald 2008; Jaiswal et al.

2010). This model proposes distributions of residential and non-residential building classes for urban and rural areas, at a national scale. Various sources of information on buildings were harmonised in this initiative, and national mapping schemes were applied to infer structural building classes from available data, leading to methods that are still being used in the current exposure modelling efforts in Europe.

The Global Exposure Database from the Global Earthquake Model (GED4GEM) provides a spatial inventory of residential buildings and population for the purposes of seismic risk modelling and earthquake loss estimation (Gamba 2014). Data is available at up to three different geographical scales (national and administrative boundaries 1 and 2) and the sources of information depend on the selected scale. The open datasets used to populate GED include the Database of Global Administrative Areas (GADM), the Global Rural-Urban Mapping Project (GRUMP), the Gridded Population of the World (GPW), the Multiple Indicator Cluster Surveys (MICS), UN Habitat's Global Urban Observatory (GUO) data, United Nations statistics, the aforementioned PAGER building inventory database, among others. The GED database is publicly available through the OpenQuake-platform (OpenQuake n.d.). Another global initiative that covers building inventories is the World Housing Encyclopedia (WHE 2014). Detailed housing reports from all over the world are publicly available and include information about the building type, construction practice, average floor areas, average construction cost, and a qualitative estimation of building vulnerability under seismic events. However, the WHE reports do not cover the number of buildings in each country nor the associated geographical distribution, and thus cannot be used alone to develop exposure models.

At a regional level, the first efforts to develop a European residential exposure model began in the European FP6 NERIES project, based on land use cover and population distributions. The countrywide approximated building database for 27 countries in Europe was obtained from CORINE Land Cover and population databases from 2000. The methodology used in obtaining the country basis geographic distribution of the number of buildings from CORINE Land Cover and Population databases is described in Appendix A of BU-KOERI (2010). Once the gridded distribution (at 150 arc seconds) of the total number of buildings was obtained, the approximate number of buildings in each building class was computed using the national building class ratios provided in the aforementioned PAGER database.

Within the European FP7 NERA project, further progress on the development of a European model of the residential building stock was made by collecting building stock information at a national level from housing censuses and national records on construction practices performed by statistical or financial services of the country (Crowley et al. 2012). Some countries (e.g. Italy, Portugal, Turkey) were found to have sufficient data to directly distribute the buildings in terms of structural building classes, whereas in other countries, the data available from the housing censuses (such as occupancy type, date of construction, number of stories and main construction material) was mapped to building classes through expert judgment-based mapping schemes. The final distributions of residential building classes at different geographical levels within each European country were included within the aforementioned GED4GEM database. This model was taken as the starting point for the European Exposure Model presented herein and has been updated with more recent census data and mapping schemes created by local experts for residential buildings, as described in Deliverable D26.2 (Crowley et al., 2018). This deliverable describes the extension of the European exposure to non-residential (commercial and industrial) buildings, as well as the current status of the residential exposure model development. This deliverable therefore provides an overview of the complete European exposure model methodology as of April 2019.

1.1.3 Methodology

The development of a European exposure model, i.e. the spatial distribution of the residential, commercial and industrial building count, population, and replacement cost - characterized in terms of building classes - follows two main steps: i) modelling the distribution of the number of buildings across different building classes within urban and rural areas, and in some cases also historical centres and large cities, ii) modelling the spatial distribution of the number of buildings, replacement cost and number of occupants (for residential buildings) within each building class across a given country, by combining a number of different public sources of data. The residential and non-residential exposure models have been derived based on the latest national housing censuses, socio-economic indicators (e.g. labour force, population and floor area per worker per economic sector), and mapping schemes (also referred to as inference rules) developed by the authors together with local experts. For each version of the European Exposure Model that is released, the associated sources of data are documented and can be downloaded from an Excel sheet available on the following webpage: https://eu-risk.eucentre.it/exposure.

2 Building Class Distribution

This Chapter provides a summary of the classification of residential, industrial and commercial building classes in the European exposure model, and the methods used to distribute the buildings in Europe between these classes.

2.1 Building Classes

The buildings in the exposure model are classified according to their seismic performance using a building taxonomy that is based on an updated version of an international standard (the GEM Building Taxonomy, Brzev et al. 2013, as updated by Silva et al. 2018) that allows buildings to be classified according to a number of structural attributes. The main attributes that have been selected for the consistent definition of building classes across Europe are as follows:

- Main construction material (reinforced concrete, unreinforced masonry, reinforced/confined masonry, adobe, steel, timber).
- Lateral load resisting system, LLRS (infilled frame, moment frame, wall, dual frame-wall system, flat slab/plate or waffle slab, post and beam).
- Number of storeys.
- Seismic design code level (D: pre-code, C: low code, B: moderate code, A: high code).
- Lateral load coefficient used in the seismic design.

A description of some of the main residential, industrial and commercial building classes found across Europe is provided in Tables 1, 2 and 3, respectively. These building classes are classified according to the main construction material, LLRS and number of storeys. The building classes in each country are identified from local expert judgment and peer-reviewed publications, and then the population, building count and replacement cost in each country is distributed across these building classes, as described in the subsequent sections. The lateral load coefficient of engineered buildings has not yet been considered in the v0.1 exposure model, but will be included in the v0.2 model, as described subsequently herein.

Table 1. Examples of European residential building classes

RESIDENTIAL BUILDING CLASSES		DESCRIPTION
 	MUR+STRUB/LWAL/HBET:1-4 MUR+STDRE/LWAL/HBET:1-4 MUR+CL/LWAL/HBET:1-4	Unreinforced masonry (MUR) structures have commonly been used for residential buildings across Europe. In urban areas, these buildings comprise usually multiple housing units with 2 to 4 storeys, while in rural areas it is more common to find single dwellings with 1 or 2 storeys. The lateral load resisting system (LLRS) is characterized by unreinforced masonry walls (LWAL) in both directions. Walls are frequently made of fired clay solid or hollow bricks (CL) with lime or cement mortar or rubble (STRUB) / dressed (STDRE) stone in mud/lime mortar (or without mortar).
	MCF/LWAL/ HBET:1-4	Confined masonry (MCF) structures are found in both urban and rural areas in some parts of Europe. The LLRS is characterized by unreinforced masonry walls confined with cast-in-place reinforced concrete (CR) tie columns and beams, which are built at regular intervals. The walls are commonly made of clay units or concrete blocks, and the CR elements are usually cast after the masonry walls have been constructed.
	CR/LFM/HBET:3-7 CR/LFINF HBET:3-7 CR/LFLS/HBET:3-7 CR/LFLSINF/HBET:3-7	Reinforced concrete frame (LFM) or CR infilled frame (LFINF) buildings (which may in some cases be constructed with flat slabs and no beams) are generally used for multiple housing units in urban areas of Europe. The LLRS is characterized by CR frames made of columns and beams (usually) with (or without) masonry-infill walls and cast-in-place CR floor slabs. Infilled walls are generally made of fired clay hollow bricks. These buildings typically have from 3 to 7 storeys. In some cases, the ground floor of these buildings is not constructed with infill panels (for parking space, or commercial activities), and are thus prone to developing a soft storey. These buildings are usually designed following code standards, though the year of construction and associated seismic design codes will have an influence on the level of material, member and system ductility, and thus on the seismic performance.

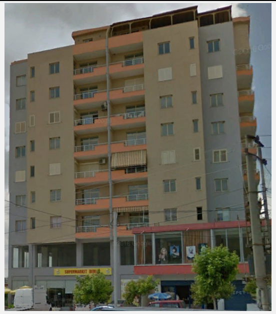
	CR/LDUAL/HBET:6-15 CR/LWAL/HBET:6-15	Reinforced concrete dual frame-wall (LDUAL) or CR wall residential buildings are generally multiple housing units found in the major urban areas of Europe. These buildings typically have 6 to 15 storeys. The LLRS comprises columns, beams and walls (or only walls) and the slabs are often comprised by either pre-fabricated beams with a layer of concrete or reinforced concrete cast-in-place. These buildings are usually designed following code standards, though the year of construction and associated seismic design code will have an influence on the level of material, member and system ductility, and thus on the seismic performance.

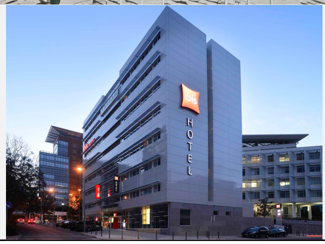
Table 2. Examples of European industrial building classes

INDUSTRIAL BUILDING CLASSES		DESCRIPTION
	CR+PC/LPB/HBET:1-3 CR+PC/LFM/HBET:1-3	A very common typology used for the construction of industrial buildings in Europe is characterized by the use of precast reinforced concrete. These buildings are usually low-rise (in the majority single storey), rectangular in plan, with precast cladding panels for the exterior walls. The majority of the precast industrial buildings found in Europe are not seismically designed and are commonly characterized by a poor connection between the beams and columns and thus can be described with a post and beam (LPB) LLRS.
	S+SR/LFM/HBET:1-3	Steel portal frames (S/LFM) are commonly used for industrial purposes across the European countries. Portal frames typically use hot-rolled (SR) beams and columns for the roof rafters and supporting columns, although cold formed sections may be adequate for some small span structures. They come in a variety of different shapes and sizes, with flat or pitched roofs. The majority of the industrial buildings (light industry) found in Europe seem to be low-rise, with height up to 5 m, with single-span symmetrical portal frame up to 25 m. Portal frames provide sufficient in-plane stability, and thus only require bracing (or infills) for out-of-plane stability.

	S/LFM/RME/HBET:1-3	The main alternative to portal frames found in Europe is lattice construction. Roof lattice trusses (RME) constitute a typical solution for large spans (>30 m) and for buildings of shorter spans, where there is a significant amount of mechanical plant or machineries suspended from the roof area. Lattice trusses tend to be beam and column structures and are rarely used in portal frames. Using lattice structures, a comparatively high stiffness and load bearing resistance can be achieved, while minimizing material use.

Table 3. Examples of European commercial building classes

COMMERCIAL BUILDING CLASSES		DESCRIPTION
	CR+PC/LPB/H:1 CR+PC/LFM/H:1	This type of building can be seen across Europe as detached shops, typically used for hairdressers, car sales and maintenance, large and small retail, shopping centres, department stores, service stations, food shops and other wholesale and retail. The main construction material is precast concrete (CR+PC) typically varying from 1 to 2 storeys. The LLRS includes columns and beams connected by cast-in-place CR floor slabs.
	CR/LFINF/H:2 CR/LFM/H:2	This type of building is normally found across Europe as detached shops, as described above. They are usually constructed with reinforced concrete infill frames or reinforced concrete frames. The LLRS is characterized by columns and beams, with (or without) masonry-infill walls, that support CR floor slabs. Infill walls are generally made of fired clay hollow bricks.
	CR/LWAL/HBET:3-5 CR/LDUAL/HBET:3-5 CR/LWAL/HBET:6- CR/LDUAL/HBET:6-	These CR dual frame-wall or CR wall office buildings are commonly used by banks, insurance companies, research institutions, engineering companies, etc. The LLRS comprises columns, beams and walls (or only walls) connected by cast-in-place CR floor slabs. These buildings have 3 to 5 storeys or more than 6 and are usually designed following code standards. The year of construction and associated seismic design code will have an influence on the level of material, member and system ductility, and thus on the seismic performance.

 	CR/LFINF/HBET:3-5 CR/LWAL/HBET:3-5 CR/LDUAL/HBET:3-5 CR/LFINF/HBET:6- CR/LWAL/HBET:6- CR/LDUAL/HBET:6-	Buildings used for accommodation commonly vary from 3 to 5 or more than 6 storeys. Although both can be found all over Europe, the taller are typically found in urban areas. The LLRS of CR infill frame buildings is characterized by columns and beams, with (or without) masonry-infill walls, that support CR floor slabs. Infill walls are generally made of fired clay hollow bricks. The LLRS of CR wall buildings comprise columns, beams and walls (or only walls) connected by cast-in-place CR floor slabs. These buildings are usually designed following code standards. The year of construction and associated seismic design codes will have an impact in terms of the seismic performance.
	CR/LFINF/HBET:3-5 CR/LFM/HBET:3-5 CR/LFINF/HBET:6- CR/LFM/HBET:6-	This type of reinforced concrete infill frame or bare frame office building is found all over Europe and is used by banks, insurance companies, research institutions, engineering companies, etc. These buildings have 3 to 5 storeys or more than 6 storeys. The latter are usually present in large urban areas. The LLRS is characterized by CR frames made of columns and beams with (or without) masonry-infill walls and cast-in-place CR floor slabs. Infill walls are generally made of fired clay hollow bricks. In some cases the ground floor of these buildings is not constructed with infill panels (used as a reception/lobby), and are thus prone to developing a soft story. These buildings are usually designed following code standards. The year of construction and associated seismic design code will have an impact in terms of the seismic performance.

2.2 Building Class Distribution for Residential Buildings

Population and housing census statistics usually provide information related to living conditions such as the number of dwellings and physical housing attributes that exist in a given area. The oldest census data used in the present European exposure model is from 2001 (for Lithuania, Luxembourg, Slovakia and the United Kingdom), and the latest is from 2017 (for Norway and the Netherlands). Some countries have detailed information on the number and characteristics of the buildings through a separate Building Census (e.g. Portugal, Turkey, Greece), but in the majority of the cases only the type of the dwelling (single-family or multi-family) or just the predominant material of the exterior walls or the year of construction is available (e.g. Moldova, Croatia).

For residential buildings, the information that is used to describe individual dwellings/buildings within national housing censuses varies across the different countries, and typically does not allow for a one-to-one mapping to the building classes described previously. By carefully exploring the information provided by the census of each country, it becomes apparent that in many cases the information within the census can be mapped to more than one building class. For example, dwellings whose predominant exterior wall material is defined in the census as 'clay bricks' could potentially be reinforced concrete infilled moment-frame, confined masonry wall or unreinforced masonry wall systems.

The type of occupancy can also be used to distinguish between building classes; for example, apartments are usually found in mid- to high-rise buildings constructed with reinforced concrete or load-bearing masonry, whereas detached or terraced single-family houses are usually low-rise and often built with unreinforced masonry. The percentage of the number of buildings in each class can be directly inferred from the material, the type of occupancy, the number of storeys, or whether the area in which they are located is urban or rural, and this can be further informed by the judgment provided by local experts. The judgment-based mapping of the available (census) data to the distribution of building classes is called a mapping scheme. The development of the mapping schemes closely follows the methodology thoroughly described in Yepes-Estrada et al. (2017). The advantage of this approach is that it can be continuously refined based on additional input from local experts.

So far, residential building mapping schemes have been developed for all European countries using both local expertise and the following sources of information: NERA project (Crowley et al., 2012); TABULA - Typology Approach for Building Stock Energy Assessment (TABULA n.d.); World Housing Encyclopedia (WHE 2014); peer-reviewed publications; GED4GEM (Openquake n.d.); PAGER building inventory database (Jaiswal and Wald 2008).

Mapping schemes are provided separately for urban and rural areas within each country, and in some cases for a third category of historical centres or large cities, such that the differences in the distribution of building classes between these areas can be captured. In many cases the census already separates the data on the number of dwellings/buildings between urban/rural areas, but when this was not provided, it has nevertheless been possible to obtain the population-based definition of urban/rural within each country from the census, such that each municipality can be assigned to the appropriate category. It is worth noting that when the census is in terms of buildings, the proposed mapping schemes directly provide the distribution of building count across the building classes, and that the distribution of the population and replacement cost across the building classes requires further considerations on the number of dwellings and built-up area per building class, as described subsequently.

2.3 Building Class Distribution for Non-Residential Buildings

Non-residential buildings fall into two broad categories: (light) industrial buildings and commercial buildings (offices, wholesale and retail trade, and hotels and restaurants). The distribution of the non-residential buildings across the most likely building classes has also been developed for each country. For industrial buildings, the European countries have been initially assigned into groups of countries with similar building stock characteristics, as suggested by Wyss et al. (2013). Subsequently, reference countries with available information on the attributes of the industrial buildings were selected for each group, based on which the building class distribution for the remaining countries within the group was developed. The main sources of information for these distributions were the census databases, peer-reviewed publications, such as Bournas et al. (2014), the PRECASTEEL project (Braconi et al. 2013), Euro-Build in Steel Project (2008) and personal communications with local experts.

The distribution of the predominant building classes associated with each one of the three aforementioned commercial categories has been developed based on local expert judgment, the residential building distributions (considering that commercial activities are often found within residential buildings) as well as satellite imagery.

As with residential buildings, the distribution of non-residential building count across building classes has first been developed, and then the built-up area per building class has been estimated to distribute the replacement cost across the building classes. In the v0.1 model the population of the non-residential buildings is not directly modelled, and only the residential population has been included in the exposure model and distributed across the residential building classes. In future versions of the model, estimates of the occupants of both residential and non-residential buildings during the day, night and transit times will be incorporated.

2.4 Design Code Type and Lateral Force Coefficient

For reinforced concrete building classes, additional attributes related to seismic design are currently being assigned based on the year of construction. A detailed study of the temporal and spatial evolution of seismic design across Europe is being undertaken in order to identify, for each country, the type of seismic code (D: absence of seismic design, C: low-code, designed for lateral resistance using allowable stress design, B: moderate code, designed for lateral resistance with modern limit state design and A: high code, designed for lateral resistance coupled with target ductility requirements) and lateral load coefficients (i.e. percentage of weight that should to be resisted laterally), for which reinforced concrete buildings from different eras in different regions within the country were designed. The lateral load coefficient has typically always been calculated by combining one or more of the following: a seismic coefficient (dependent on the seismic zonation and possibly also the soil category), a structural coefficient (dependent on the lateral load resisting system, and representing the ductility and damping characteristics), an importance coefficient (with the buildings being separated into various categories as a function of their occupancy and importance in the aftermath of an earthquake), and a dynamic coefficient (dependent on the period of vibration of the structure).

Figure 1 shows an example of the evolution of seismic design codes across Italy (from D to A) and the lateral force coefficients that were used in seismic design (predominantly for one storey buildings) across the country over different periods of time. Up until 2004 the lateral forces were explicitly prescribed in the code (or were simply calculated as a function of number of storeys and seismic zone), whereas in 2004 the seismic zonation was provided in terms of peak ground acceleration (PGA) that was used to anchor a spectral shape for different soil classes. In order to calculate lateral load coefficients for comparison with the previous maps, the PGA for each zone has been multiplied by the amplification factor for soil class B and the spectral amplification at 0.5 seconds, divided by a ductility factor of 3.5 (assumed to be a reasonable average value for reinforced concrete buildings).

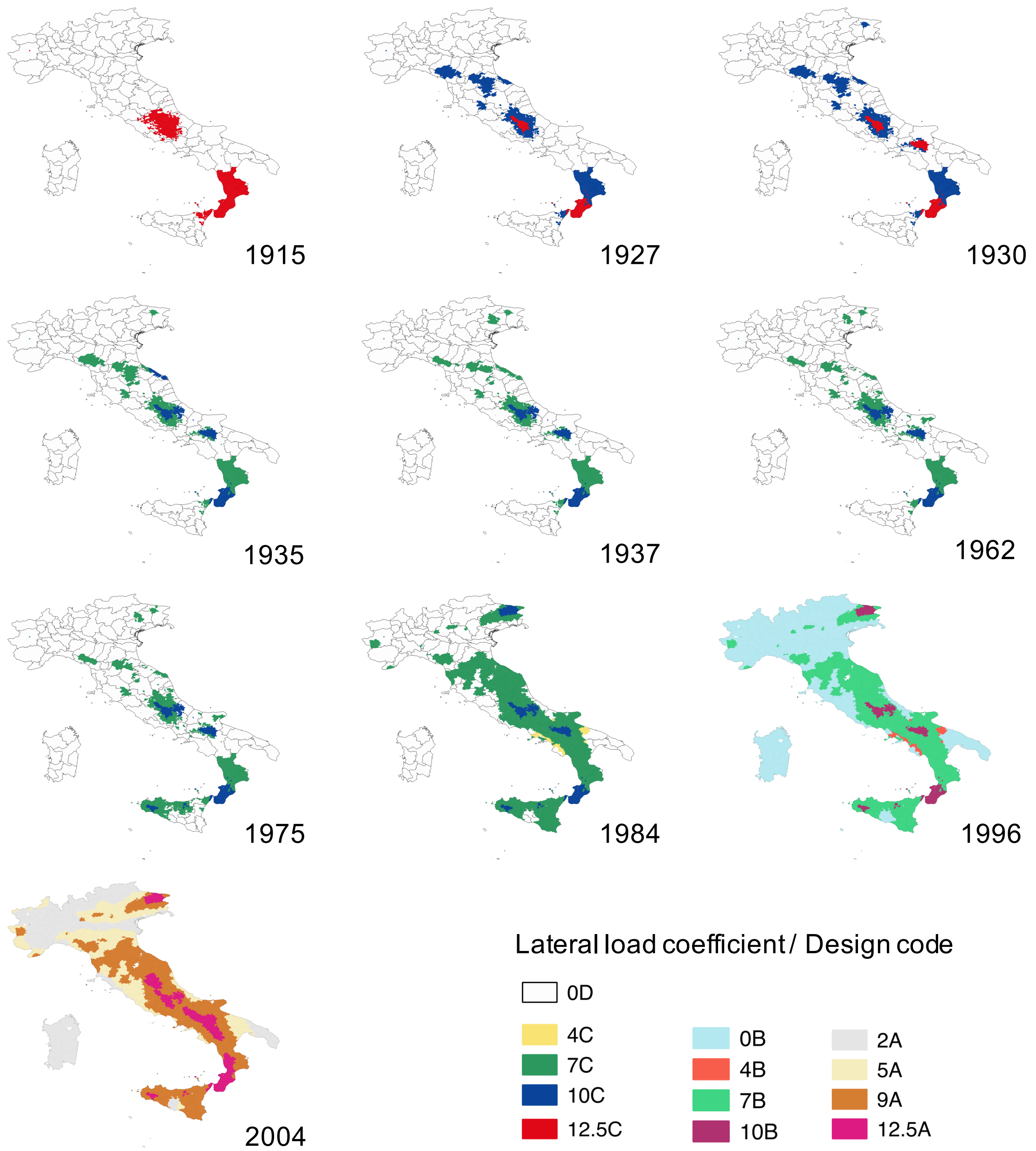


Figure 1. Evolution of seismic design codes in Italy (mainly adapted from Di Pasquale et al. 1999a; 1999b) showing the changes in lateral load coefficient (in percent) and type of design code (D to A).

Similarly, Figure 2 illustrates the evolution of seismic design codes in Serbia and the lateral force coefficients that were used in the design across the country. In Yugoslavia the first seismic code was introduced one year after the 1963 Skopje earthquake (code class C). The seismic coefficient was calculated as a function of the seismicity of the region, the type and soil quality and the coefficient of dynamic response. The code of 1964 was used until 1981, when the current code of Serbia was introduced. In this code (code class B) the seismic coefficient was calculated as a function of all of the four parameters described previously. Design code type A has not been considered as this has only very recently been introduced (through Eurocode 8), and so its impact on the exposure model is likely to be minimal.

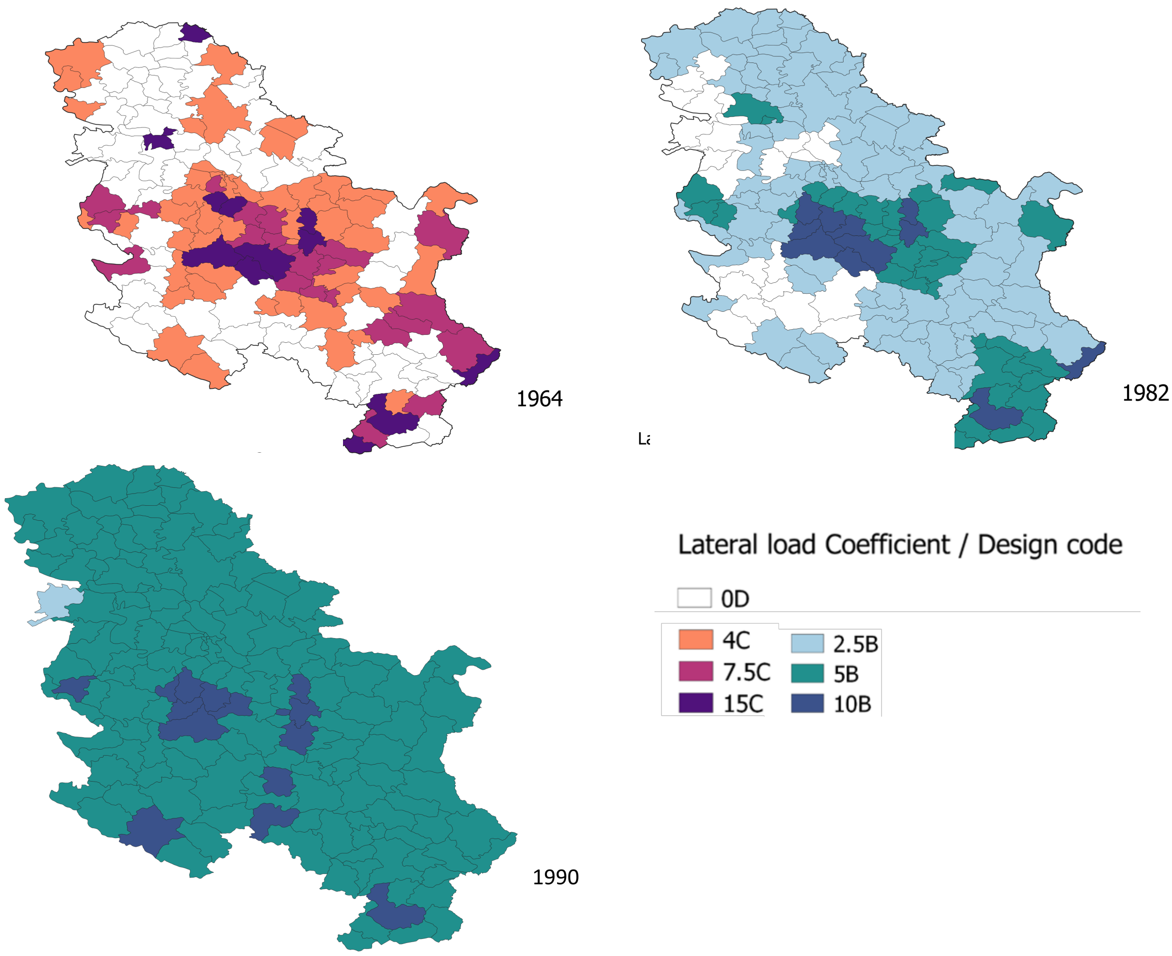


Figure 2. Evolution of seismic design codes in Serbia showing the changes in lateral load coefficient (in percent) and type of design code (D to B).

3 Spatial Distribution of Building Data

This Chapter describes the sources and methods used to estimate the total number of residential, industrial and commercial buildings across Europe, and distribute them spatially. All sources of data can be downloaded from the following electronic supplement: http://eu-risk.eucentre.it/wp-content/uploads/2019/03/European_Exposure_Model_v0.1_Sources_15-03-2019.xlsx

3.1 Spatial data on residential buildings

The public census data for all European countries has been collected at the highest level of resolution available. However, the number of residential buildings ($N_{res\_buildings}$) is often not available from the national census and thus needs to be estimated by dividing the number of dwellings ($N_{dwellings}$) by the average number of dwellings per storey ($N_{dwellings/storey}$) per building class, based on local expert feedback, and by the average number of storeys per building class ($N_{storeys/building\_class}$), by combining census data with local expert feedback, as represented in the following expression:

$$N_{res\_buildings} = \frac{N_{dwellings}}{N_{dwellings/storey} \times N_{storeys/building\_class}} \quad (1)$$

The replacement cost refers to the value of replacing a building in accordance with the latest building standards applicable for the country, and it includes the cost of the structural, non-structural components and contents (the cost of the land is not included). Since construction cost is commonly found per square meter, the average constructed area per building type is first required. The constructed area of a residential building class ($A_{res\_building\_class}$) can be obtained by multiplying the estimated number of dwellings for each building class ($N_{dwellings|building\_class}$) by the average floor area per dwelling within that building class ($A_{dwelling/building\_class}$):

$$A_{res\_building\_class} = N_{dwellings/building\_class} \times A_{dwelling/building\_class} \quad (2)$$

The average area per dwelling for each building class is defined using information such as housing census and considering that single-family detached buildings (one dwelling) tend to have larger area compared to dwellings within apartments. For example, according to data found in the Statistics Netherlands, the average area of a single-family dwelling is around 150 m^2, while a dwelling in a multi-family building (apartment) is approximately 80 m^2. Finally, a check is performed to ensure that the total calculated area is in accordance with the total residential area of each country, as reported in the associated national census or alternative sources of information (see link provided previously for all sources of data). The replacement cost per square metre is defined separately for urban and rural areas and large cities. In addition, it is further differentiated based on the main material used for construction (masonry, adobe, concrete, wood, steel), assuming that in the majority of the cases reinforced concrete is more expensive compared to steel, masonry, adobe or wood. Given that some countries have their own currency, Euros have been selected as the reference currency in order to homogenise and compare values between countries. It is worth noting that all the costs have been adjusted to represent the value of replacing a building in the reference year of 2018, using construction cost indices (for the cases where construction costs were found for a year different to 2018). The construction cost index shows the trend in the cost of new residential buildings over the years and is commonly found in the Statistical Offices of each individual country.

The population within a given residential building class in a given administrative division ($P_{res\_building\_class}$), is given by distributing the total number of people in that geographical area (P_{admin}) according to the proportion of dwellings per residential building class:

$$P_{res\_building\_class} = \frac{N_{dwellings/building\_class}}{N_{dwellings/admin}} P_{admin} \quad (3)$$

Using the above method, it is ensured that the total population available within each administrative boundary is consistent with the census data.

3.2 Spatial data on industrial and commercial buildings

Few national statistics departments provide exposure information for non-residential buildings at regional or national scale. Unlike the residential building stock, that relies predominantly on national housing census data, the industrial and commercial building stock, when not captured in a separate national building census, needs to rely on secondary sources, such as socio-economic data, studies related to the energy efficiency of buildings, European statistics platforms or the judgment of local experts.

The majority of the national census databases, with only a few exceptions (e.g., Greece, Turkey), do not provide information on the number of industrial buildings. Therefore, for the cases where no data were found, the number of industrial establishments or enterprises was used as a proxy to define the number of industrial buildings. The number of industrial establishments/enterprises is commonly found at the national level in the Structural Business Statistics of each country, categorized by industrial activity. In the current exposure model, the manufacturing, mining, quarrying and construction sectors, which are usually reported in the structural business statistics, were assumed to constitute the industrial building stock. The total area of the industrial buildings in each European country on a 30 arc seconds resolution was obtained from Sousa et al. (2017), and multiplied by the replacement cost per square metre to calculate the replacement cost of industrial buildings per administrative divisions within each country. An estimate of the total replacement cost per square metre for industrial buildings across all European countries was made by combining local expert judgment and sources such as Turner and Townsend (2018) and AECOM (2014). In order to distribute the area (and replacement cost) between the building classes, an estimate of the built-up area per industrial building class was also required. The built-up area of industrial buildings per administrative division ($A_{ind\_buildings/admin}$), obtained from the aforementioned 30 arc sec resolution grid, was also used to spatially distribute the total number of industrial buildings in the country ($N_{ind\_buildings/country}$) throughout the administrative divisions ($N_{ind\_buildings/admin}$) as follows:

$$N_{ind\_buildings/admin} = N_{ind\_buildings/country} \frac{A_{ind\_buildings/admin}}{A_{ind\_buildings/country}} \qquad (4)$$

Whilst some national statistics departments do contain information concerning the total number of commercial buildings (e.g. Norway, Italy), or the number of commercial facilities at the smallest division (e.g. Greece), the majority of countries in Europe do not. In general, the total number of commercial buildings and the total built up area was collected from the EU Buildings Database (e.g. Ireland, Latvia, Belgium) (EU Buildings Database n.d.) or using assumptions based on the number of enterprises/establishments/businesses (e.g. Albania, Portugal, Switzerland). The number of commercial facilities is usually related with the type of sector – services – and the type of business: wholesale and retail trade, repair of motor vehicles and motorcycles, accommodation and food services, information and communication, financial and insurance activities, real estate activities, administrative and support service activities, arts, entertainment and recreation and other service activities. These data are then organized according to three categories for the purposes of the European risk model: offices, wholesale and retail trade, and hotels and restaurants.

For the cases where the number of commercial facilities is only available at the national level (e.g. using EU building datasets), it is necessary to distribute these facilities within the administrative divisions of the countries in order to improve the spatial resolution of the exposure model. The assignment of the number and built-up area of each of the three categories of commercial buildings within each administrative division ($N_{comm\_buildings/admin}$) relies essentially on economic census surveys, which provide demographic data concerning the workforce per commercial activity, such as the number of employees for each administrative division ($N_{employees/admin}$). Following this approach, the number of commercial buildings was calculated as follows:

$$N_{comm\_buildings/admin} = N_{comm\_buildings/country} \frac{N_{employees/admin}}{N_{employees/country}} \tag{5}$$

Similarly, the area of commercial buildings within each administrative division ($A_{ind\_buildings\_admin}$) was calculated, and multiplied by the total replacement cost per square metre (obtained from various sources, such as those provided above for industrial buildings). In order to distribute the area (and replacement cost) between the building classes, estimates were again made on the built-up area per commercial building class.

4 Uncertainties in Exposure Modelling

As described in the previous sections, the development of the European exposure model leverages on housing census surveys and socio-economic data, which are sources of information that, in the vast majority of cases, have not been created for this purpose. Consequently, several assumptions have to be adopted in order to produce a dataset capable of providing the geographical location, built-up area, replacement cost, building class and number of occupants for each asset in the region of interest. The Scientific Advisory Board's mid-term review (SAB, 2018) highlighted the importance of evaluating the uncertainties in the exposure model and so specific activities on this aspect have been initiated.

Some of these sources of uncertainty can be categorized as epistemic since with additional knowledge they could be reduced or even neglected. For example, the variability in the definition of the probabilities associated with each building class in the mapping schemes can be considered epistemic. This source of variability could be reduced by collecting additional ground truth information in order to understand to which building classes each combination of attributes actually corresponds. Alternatively, this source of variability can be propagated to the exposure results by considering different mapping schemes, each one defined by a different expert or set of experts. This process can be compared to the definition of logic trees for ground-motion prediction equations (GMPE) or seismogenic models, which have traditionally been based on combining a number of different models with expert judgment-based weights. Future studies will look at various ways of modelling this epistemic uncertainty in order to understand the impact it has on the resulting risk metrics.

Other parameters required for the derivation of exposure models can be considered as random variables (i.e. aleatory variability), for the purposes of propagating their dispersion through to the risk results. These include the average area per dwelling, the average replacement cost per square metre and the number of dwellings per building class. Although the variability of these parameters has not been thoroughly investigated in the past, it is possible to define some parametric distributions based on existing data for some European countries.

To this end, a large amount of data has been collected for five European countries characterized by moderate to high seismic hazard: Portugal, Spain, Italy, Greece and Slovenia. It is fundamental to ensure that the data covers the entire country and it is defined at a small administrative division. This approach avoids the underestimation of the dispersion, which could arise from significant spatial aggregation (and thus averaging) of each parameter. One of the most reliable and comprehensive sources of information for this type of data is the National Statistical Office from each country. For the definition of the variability in the average area per dwelling, information concerning the useful floor space per dwelling was collected at the smallest administrative level for all five countries. The evaluation of the distribution of this parameter indicates an average coefficient of variation of 21%. For example, the statistical analysis for Portugal indicated a value of 21.2% while Greece led to a value of 20.5%. The National Statistical Offices also provide information regarding the construction costs for each country. However, this information was only available at the national level or at the first administrative division.

Such level of aggregation does not allow modelling the variability in the construction costs within each country. As an alternative, for each country 200 construction costs were randomly collected from real estate agencies for residential buildings, for three development types: cities, urban areas and rural areas. Clearly the costs from real estate agencies reflect the commercial value and not the construction costs. However, the purpose of this exercise is solely to evaluate the variability in the costs, and not the average costs. This set of values were used to estimate a coefficient of variation for each development type, leading to values of 39%, 53% and 37% for cities, urban areas and rural areas, respectively. These results indicate a similar dispersion in the costs for cities and rural areas, which is somehow expected as the building classes do not differ significantly within each: new construction in cities is mostly represented by modern mid- to high-rise reinforced concrete buildings whilst in rural areas low-rise masonry or single-dwelling reinforced concrete continue to be the main construction type. On the other hand, urban areas can be characterized by a wide range of building classes, spanning from costly modern high-rise buildings to cost-efficient housing, thus leading to a greater coefficient of variation. These sources of variability are currently being incorporated into the European seismic risk calculations in order to identify which parameters are driving the variability in European seismic risk, and plan for the communication of these uncertainties. The final year of the work package focuses on verification and validation and more focus on the evaluation of uncertainties in the exposure model will also be made and included in the final deliverable D26.8.

5 SERA European Exposure Model v0.1

5.1 Summary Statistics and Maps

The statistics of the current version of the European Exposure Model (v0.1) are shown in Table 4. These data have been incorporated into three different interactive exposure model viewers available from the European Seismic Risk Service (https://maps.eu-risk.eucentre.it/). One of the viewers shows the population, building count and replacement cost on a hexagonal grid, with a spacing of 0.30 x 0.34 decimal degrees (approximately 1,000 km^2 at the equator) (developed using the methodology described in Silva et al. 2019) (Figure 3). A second viewer shows the national distribution of population, building count and replacement cost according to the main construction material of the building classes (Figure 4), and the third viewer presents the population, building count and replacement cost (including the contents) within each administrative level 1 boundary in Europe (shown in Figure 5). Future versions of these viewers will also allow the national exposure models in the OpenQuake-engine format (Silva et al. 2014; Pagani et al. 2014) to be downloaded.

Table 4. Statistics of v0.1 European exposure model (rounded to nearest hundred)

Country	Number of residential buildings	Number of non-residential buildings	Replacement - cost - Residential [Euro million]	Replacement cost – Non-Residential [Euro-million]	Population (at date of latest census)
Albania	598,300	54,200	19,020	7770	2,800,100
Andorra	12,600	7,500	2010	6400	65,400
Austria	2,191,300	129,200	657,370	401,740	8,375,200
Belarus	1,630,300	113,900	220,530	57,150	9,991,900
Belgium	3,681,800	170,400	606,870	656,930	11,000,600

Country	Number of residential buildings	Number of non-residential buildings	Replacement - cost - Residential [Euro million]	Replacement cost – Non-Residential [Euro-million]	Population (at date of latest census)
Bosnia and Herzegovina	1,078,200	35,100	43,750	12,990	3,490,700
Bulgaria	2,060,700	160,100	152,780	124,900	7,364,600
Croatia	1,611,500	60,300	186,270	65,600	4,284,900
Cyprus	263,800	17,400	73,220	22,010	840,400
Czechia	2,184,300	216,400	430,530	325,080	8,603,000
Denmark	1,536,300	160,900	756,760	676,140	5,778,600
Estonia	212,100	24,700	47,690	46,650	1,315,600
Finland	1,236,900	116,900	434,890	425,740	5,513,100
France	14,202,300	980,300	5,389,770	2,869,430	64,027,600
Germany	18,922,600	1,044,600	5,837,580	3,863,420	80,210,000
Gibraltar	4,000	1,500	1100	2150	26,400
Greece	3,030,600	301,000	508,250	198,410	10,777,900
Hungary	2,702,200	152,700	186,350	141,170	9,773,800
Iceland	52,500	17,000	31,320	36,750	321,000
Ireland	1,854,300	82,500	371,670	256,670	4,761,900
Isle of Man	15,600	4,500	5030	4650	73,800
Italy	12,187,700	916,600	2,183,890	1,020,110	60,458,400
Kosovo	247,700	54,000	9910	6960	1,739,800
Latvia	349,800	39,400	73,630	63,430	2,003,000
Liechtenstein	10,400	4,300	3370	9760	33,400
Lithuania	507,500	101,700	92,360	160,400	2,816,600
Luxembourg	119,600	11,300	35,010	39,970	590,700
Malta	94,400	23,600	13,490	12,860	405,000
Moldova	830,400	34,600	47,530	15,390	2,804,800
Monaco	9,200	1,000	5550	3220	28,400
Montenegro	145,700	16,400	15,080	13,700	620,100
Netherlands	4,861,700	400,800	1,424,400	1,040,900	17,181,100
Norway	1,534,900	261,600	1,073,330	590,970	5,258,300
Poland	6,314,900	767,500	921,280	965,520	38,484,100
Portugal	3,368,500	249,200	420,700	137,330	10,045,700
North Macedonia	446,200	63,600	33,220	26,380	2,022,500
Romania	5,260,300	289,500	237,350	164,930	20,356,300
Serbia	2,272,400	92,900	121,580	68,170	8,926,700
Slovakia	862,300	136,200	112,240	112,930	5,379,500
Slovenia	463,000	54,600	60,730	42,510	1,964,000
Spain	9,731,000	808,000	2,047,250	693,960	46,815,900
Sweden	2,021,200	388,100	1,623,600	1,518,100	9,476,100
Switzerland	1,730,400	145,500	944,340	399,560	8,419,600
Turkey	8,355,300	974,400	2,175,180	468,120	80,810,500
Ukraine	12,188,800	554,900	857,620	406,180	51,725,500
United Kingdom	14,668,200	804,700	4,332,240	2,387,260	59,825,800

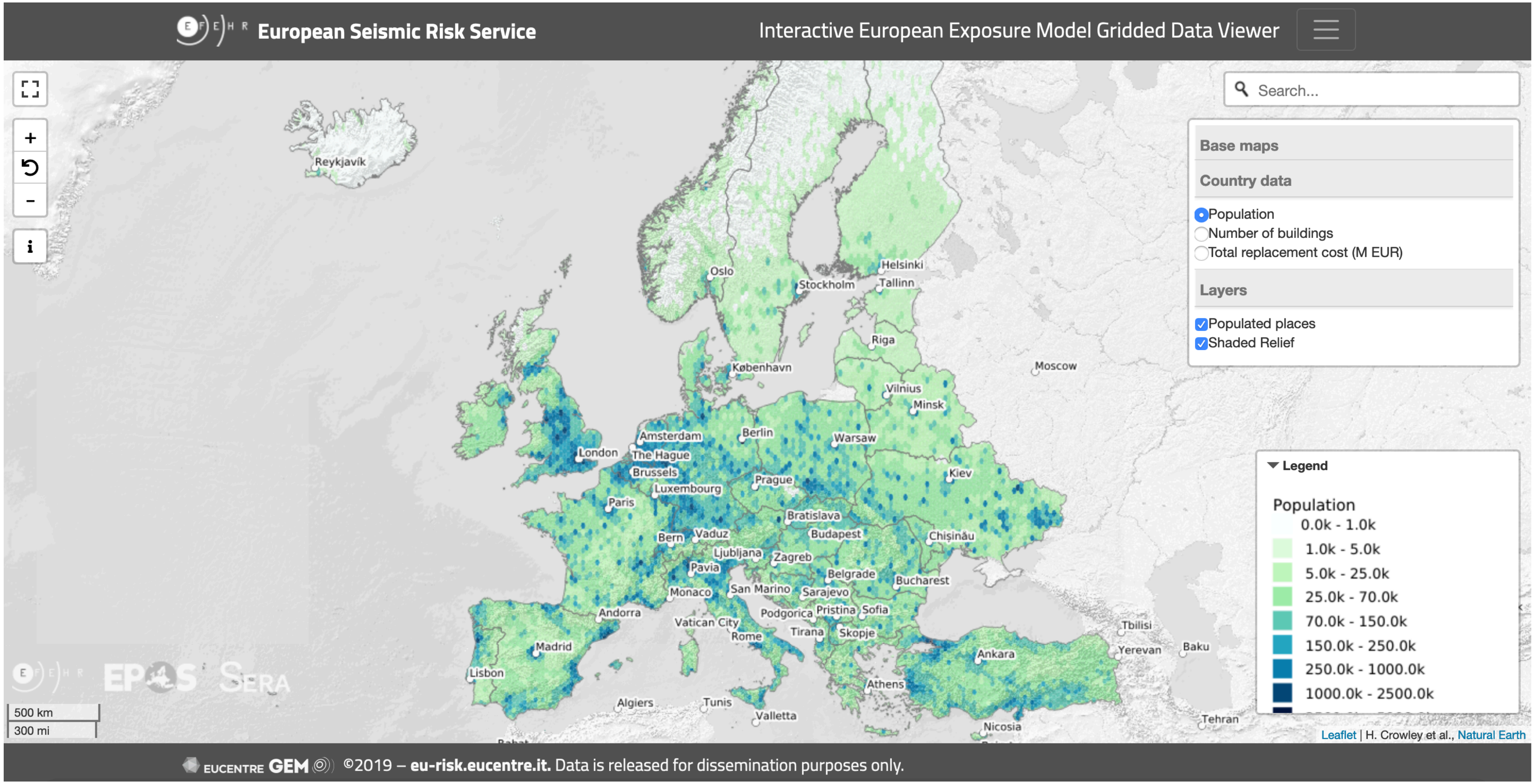


Figure 3: Screenshot of the European exposure model gridded data viewer (https://maps.eu-risk.eucentre.it/map/european-exposure-gridded-data)

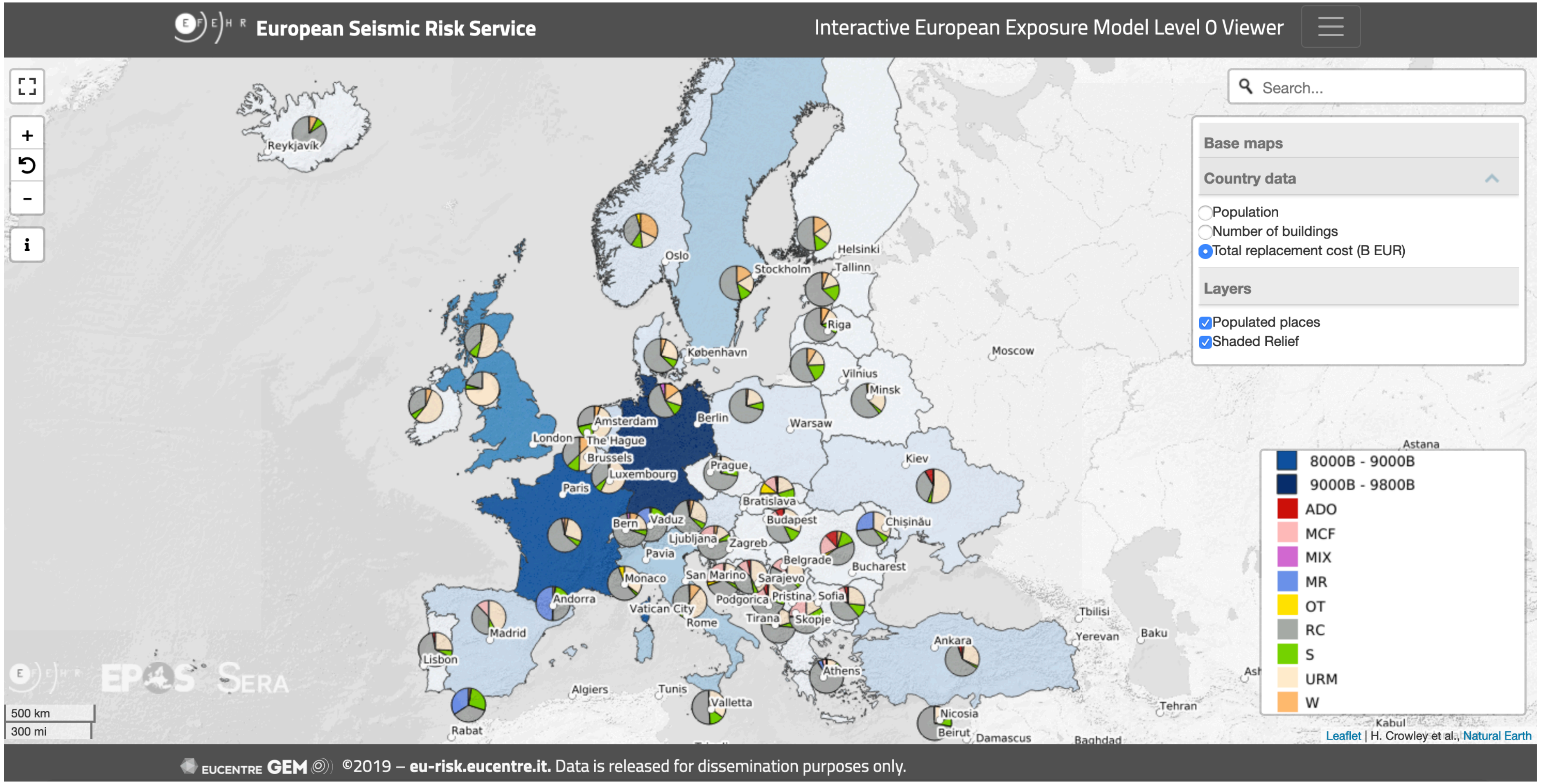


Figure 4: Screenshot of the level 0 exposure model viewer (https://maps.eu-risk.eucentre.it/map/european-exposure-level-0)

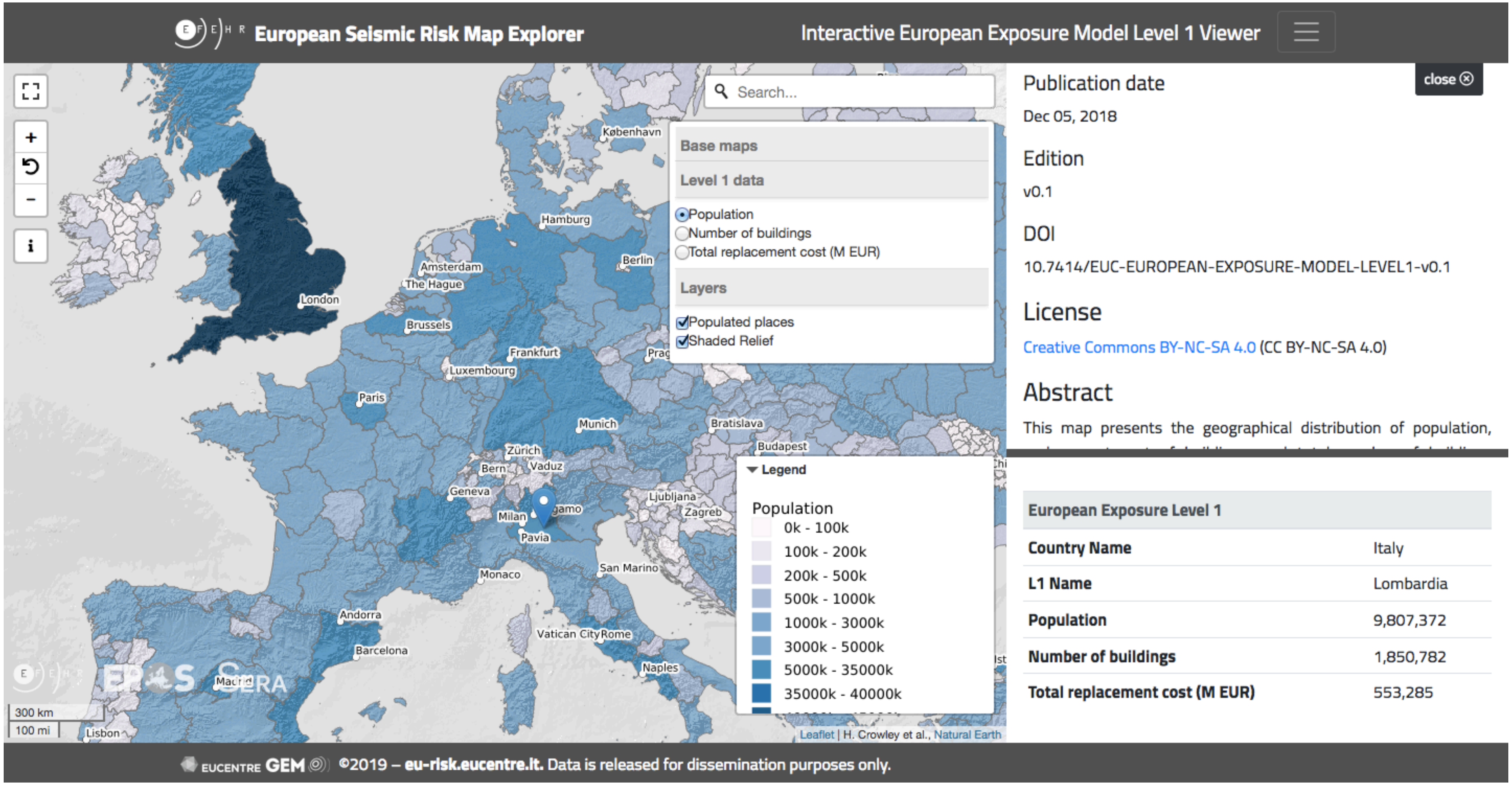


Figure 5: Screenshot of the level 1 exposure model viewer (https://maps.eu-risk.eucentre.it/map/european-exposure-level-1)

5.2 Exposure of People and Buildings to Seismic Hazard in Europe

As mentioned previously, the v0.1 of the European exposure model has been used in GEM's global risk model (GEM 2018). As part of the risk analyses, an assessment of the number of people, buildings and replacement cost that are exposed to different levels of ground shaking hazard across Europe has been undertaken (Figure 4). These analyses make use of the peak ground acceleration on reference rock with a 475-year return period, as provided by the European Seismic Hazard Model (ESHM13: Woessner et al. 2013). Figure 4 shows that a larger percentage of the total European residential population is exposed to moderate levels of hazard (0.1g to 0.2g) than the percentage of the total replacement cost, despite the fact that both replacement cost and population are directly correlated with the built-up area. This is likely to be because the buildings in these areas of hazard have low relative economic value (in relation to other areas of Europe) but are highly populated. Almost 35% of the total European residential population is exposed to PGA values of at least 0.1g, which highlights the importance of undertaking efforts to assess (and mitigate) the risk of the European buildings and their population.

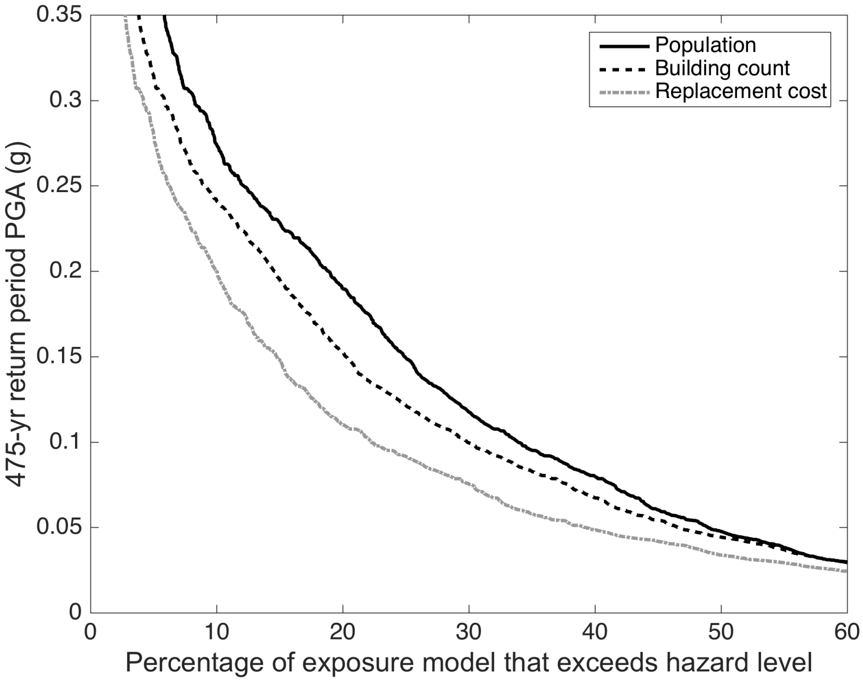


Figure 6. Percentage of population (residential), building count and replacement cost across Europe that are exposed to hazard levels that exceed given levels of PGA (g) with a 475-year return period

6 Conclusions

A model of the distribution of buildings, their value and their occupants across Europe for the purposes of seismic risk assessment has been presented herein. The current version of the model (v0.1) has been integrated within the GEM's Global Exposure Map (v2018.1). The datasets employed to develop this exposure model have been publicly provided through national institutions and local experts, and have been combined and integrated in a process that relies on various sources of expert judgment. The European Exposure Model is intended to be a dynamic product such that it may be updated as and when new datasets, feedback and models become available. Releases of updated versions of the European Exposure Model are anticipated on a regular basis and will be made available through the

European Seismic Risk Services platform (https://eu-risk.eucentre.it/). In addition to the improvement of the datasets, a key activity going forward will be to continue to assess the various sources of uncertainty in the exposure model and the impact that they have on the resulting risk estimates, as part of the ongoing activities to develop a European Seismic Risk Model (ESRM20) during the final year of the project.

7 Acknowledgements

A full list of contributors to the exposure model is provided here: https://eu-risk.eucentre.it/contributors/#exposure and all those that have contributed are gratefully acknowledged.

8 References

AECOM 2014. Available at https://www.aecom.com/ca/wp-content/uploads/2015/10/Blue-Book-2014.pdf.

Bournas, D.A., Negro, P., and Taucer, F.F., 2014. Performance of industrial buildings during the Emilia earthquakes in Northern Italy and recommendations for their strengthening, *Bull Earthquake Eng* **12**, 2383–2404. https://doi.org/10.1007/s10518-013-9466-z.

Braconi, A., Osta, A., Dall'Asta, A., Leoni, G., Möller, S., Hoffmeister, B., Karamanos, S.A., Varelis, G., Alderighi, E., Coscetti, C., Salvatore, W., Gracia, J., Bayo, E., Mallardo, R., Bianco, L., Filipuzzi, P., Vasilikis, D., Tsintzos, P., Estanislau, S., Lobo, J., Fulop, L., and Hradil, P., 2013. *Prefabricated steel structures for low-rise buildings in seismic areas*. Precasteel, Final report prepared for the European Commission.

Brzev, S., Scawthorn, C., Charleson, A.W., Allen, L., Greene, M., Jaiswal, K., and Silva V., 2013. *GEM Building Taxonomy Version 2.0*, GEM Technical Report 2013-02 V1.0.0, 188 pp., GEM Foundation, Pavia, Italy, doi: 10.13117/GEM.EXP-MOD.TR2013.02.

BU-KOERI, 2010. *Earthquake loss estimation routine-ELER v3.0*, Technical manual.

Crowley, H., Özcebe, S., Spence, R., Foulser-Piggott, R., Erdik, M., and Alten, K., 2012. Development of a European Building Inventory Database, *Proceedings of 15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

Crowley, H., Despotaki, V., Silva, V., Pitilakis, D., Pitilakis, K., Hancilar, U., Bursi, O., Wenzel, M., di Filippo, R., and Castro, M. 2017. *Deliverable D26.1 Taxonomy of European residential, commercial, industrial buildings and industrial plants*, SERA Deliverable, available at URL: https://eu-risk.eucentre.it/exposure/.

Crowley H., Rodrigues D., Despotaki V., Silva V., Covi P., Pitilakis K., Pitilakis D., Riga E., Karatzetzou A., Romão X., Castro J.M., Pereira N., Hancilar U. 2018. *Deliverable D26.2 Methods for developing Euyropean residential exposure models*, SERA Deliverable, available at URL: https://eu-risk.eucentre.it/exposure/

Crowley, H., Despotaki, V., Rodrigues, D., Silva, V., Toma-Danila, D., Riga, E., Karatzetzou, A., Fotopoulou, S., Zugic, Z., Sousa, L., Ozcebe, S., and Gamba, P., 2019. Exposure Model for European Seismic Risk Assessment, *Submitted to Earthquake Spectra*

Di Pasquale, G., Fralleone, A., Pizza, A.G., and Serra, C., 1999a. Synthesis of the code evolution from the Royal Decree issued after the Messina and Reggio earthquake up to the first Ministry decree issued after the law n. 64/74. In *La classificazione e la normativa sismica italiana dal 1909 al 1984*, De Marco, R. and Martini, M. G. (eds.) Istituto Poligrafico e Zecca dello Stato, Roma.

Di Pasquale, G., Fralleone, A., Pizza, A. G., and Serra, C., 1999b. Relevant changes to the Italian Seismic Code from 1909 to 1975 – a synoptic table. In *La classificazione e la normativa sismica italiana dal 1909 al 1984*, De Marco, R. and Martini, M. G. [eds.] Istituto Poligrafico e Zecca dello Stato, Roma.

Euro-Build in Steel Project, 2008. *Best Practice in Steel Construction, Industrial Buildings*, The Steel Construction Institute.

EU Buildings Database, n.d. Available at https://ec.europa.eu/energy/en/eu-buildings-database.

Gamba, P., 2014. *Global Exposure Database: Scientific Features*, GEM Technical Report 2014-10 V1.0.0, 46 pp., GEM Foundation, Pavia, Italy, doi: 10.13117/GEM.EXP-MOD.TR2014.10.

GEM, 2018. Available at www.globalquakemodel.org/gem.

Jaiswal, K.S., and Wald, D.J. 2008. *Creating a global building inventory for earthquake loss assessment and risk management*, U.S. Geological Survey Open-File Report-1160.

Jaiswal, K., Wald, D., and Porter, K., 2010. A Global Building Inventory for Earthquake Loss Estimation and Risk Management, *Earthquake Spectra* **26**, 731–748.

Kleist, L., Thieken, A.H., Köhler, P., Müller, M., Seifert, S., Borst, D., and Wener, U., 2006. Estimation of the regional stock of residential buildings as a basis for a comparative risk assessment in Germany, *Natural Hazards and Earth System Sciences*, **6**, 541-552.

OpenQuake n.d. Available at http://platform.openquake.org/exposure.

Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V., Henshaw, P., Butler, L., Nastasi, M., Panzeri, L., Simionato, M., Viganò, D., 2014. OpenQuake Engine: An open hazard (and risk) software for the Global Earthquake Model, *Seismological Research Letters*, **85**, 692-702.

Scientific Advisory Board, 2018. *D1.4. Mid-term report of the Scientific Advisory Board*, SERA Deliverable.

Silva, V., Crowley, H., Pagani, M., Monelli, D., and Pinho, R. 2014. Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment, *Natural Hazards*, doi:10.1007/s11069- 013-0618-x.

Silva, V., Yepes-Estrada, C., Dabbeek, J., Martins, L., Brzev, S. (2018) "GED4ALL - Global Exposure Database for Multi-Hazard Risk Analysis – Multi-Hazard Exposure Taxonomy," GEM Technical Report 2018-01, GEM Foundation, Pavia, Italy.

Silva, V., Amo-Oduro, D., Calderon, A., Costa, C., Dabbeek, J., Despotaki, V., Martins, L., Pagani, M., Rao, A., Simionato, M., Viganò, D., Yepes-Strada, C., Acevedo, A., Crowley, H., Horspool, N., Jaiswal, K., Journeay, M., and Pittore, M., 2019. Development of a Global Seismic Risk Model, *Submitted to Earthquake Spectra*

Sousa, L., Silva, V., and Bazzurro, P., 2017. Using Open-Access Data in the Development of Exposure Data Sets of Industrial Buildings for Earthquake Risk Modeling, *Earthquake Spectra* **33**, 63-84.

TABULA n.d. Available at http://episcope.eu/iee-project/tabula/.

Turner and Townsend 2018. Available at www.turnerandtownsend.com/media/3352/international-construction-market-survey-2018.pdf.

World Housing Encyclopedia (WHE), 2014. Housing Reports, available at http://db.world-housing.net/.

Woessner, J., Danciu, L., Giardini ,D., Crowley, H., Cotton, F., Grunthal, G., Valensise, G., Arvidsson, R., Basili, R., Demircioglu, M., Hiemer, S., Meletti, C., Musson, R., Rovida, A., Sesetyan, K., and Stucchi, M., 2015. The 2013 European Seismic Hazard Model - Key Components and Results. *Bull Earthquake Eng*, **13**, 3553-3596, doi:10.1007/s10518-015-9795-1.

Wyss, M., Tolis, S., Rosset, P., and Pacchiani, F., 2013. *Approximate model for worldwide building stock in three size categories of settlements*, Technical report prepared for GAR 2013. ISDR, Geneva, Switzerland.

Yepes-Estrada, C., Silva, V., Valcárcel, J., Beatriz Acevedo, A., Tarque, N., Hube, M. A., Coronel, G., and Santa María, H. 2017. Modeling the Residential Building Inventory in South America for Seismic Risk Assessment, *Earthquake Spectra*, **33**, 299-322 doi: https://doi.org/10.1193/101915EQS155DP.

Contact

Project lead	ETH Zürich
Project coordinator	Prof. Dr. Domenico Giardini
Project manager	Dr. Kauzar Saleh
Project office	ETH Department of Earth Sciences
	Sonneggstrasse 5, NO H62, CH-8092 Zürich
	sera_office@erdw.ethz.ch
	+41 44 632 9690
Project website	www.sera-eu.org