# WP 1 – BE and SUOD: State of the Art (SoA), risks and human behavior

**T1.2 - SoA of earthquake (SUOD) impact on BE and related earthquake-induced modifications due to building/aggregate and aggregate/public spaces interfering conditions. Current risk-reduction strategies analysis. Definition of human behavior including crowding conditions by combining SoA data and real-world events analysis**

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## Abstract

The present D1.2.1 deals with the discussion of the seismic risk of the BE with the aim of developing a seismic risk matrix that encompasses the three factors hazard, exposure and vulnerability, for describing the risk condition of the open space under an earthquake. The vulnerability assumes great importance, which factor that may be easily mitigated within the seismic risk analysis, due to the direct impacts in the occurrence of a seismic event; in fact, the physical damage of buildings surrounding the open space may obstruct emergency paths and make the emergency management difficult. For this reason, assessing the building vulnerability in a correct way is the first step required for quantifying the amount of debris. With this regard, clarifying a correct definition of the vulnerability of buildings it is necessary for providing a complete understanding of the construction and structural features that may affect the building behaviour under seismic events. Moreover, with the aim of achieving a complete risk assessment model, comes also the need to define reliable methodologies for hazard and exposure analysis. So that, the current report provides a broad SoA of the main approaches adopted for assessing and managing the seismic risk highlighting positive aspect and limitation of each methods, in order to identify which of them are more suitable for the aim of evaluating impacts on the BE under earthquake. The final part, especially, offers an attempt to define seismic risk levels of open spaces considering the interaction between people exposed and vulnerability of buildings due to hazard, through the identification of damage scenarios.

## Keywords

Seismic risk; seismic micronozation; human exposure; building vulnerability; vulnerability assessment methods; historical masonry buildings; damage scenario; consequences matrix.

## Approvals

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## Summary

## 1. Introduction

The academic discussion concerning seismic risk during last decade has shown a growing awareness of the need to reduce disaster risk in urban areas by adopting a wider perspective, not only focused on the local scale of single building but also on the territorial scale. In fact, the built environment of the urban city centres are complex systems that cannot be reduced to individual elements, but they include the interaction between buildings, open spaces and the functional infrastructures. When dealing with earthquakes, it is currently impossible to predict in detail when they will occur and how intense the shock will be; however, the risk and the impact on the built environment can be mitigated by reducing vulnerability and exposure in the site. Defining the vulnerability conditions of buildings before a seismic event is the key factor to enhance seismic risk reduction strategies in order to improve the resilience of building heritage in historical centres and to create safer urban settlement. In case of the most recent disruptive earthquake in many regions of Europe exposed to significant seismic hazard, the disproportion between the potential destructiveness of earthquakes, in terms of magnitude, and the devastating impacts occurred has boosted a renewed interest on safety issues. These effects can be ascribed to several factors including: the high exposure of the population, the obsolescence of many buildings, the high seismic vulnerability of the historical centres and their great concentration of cultural heritage and monuments.

So that, the BE risk evaluation requires an integrated approach for vulnerability assessment that takes into account urban aspects and specific structural building conditions. From an urban point of view, vulnerability is affected by the morphological layout of historical centres, due to the narrow and winding streets and the lack of open spaces which do not guarantee public safety conditions. On the other hand, the building vulnerability is increased by the wealth of un-reinforced masonry buildings and by their constructional peculiarities due to the historical transformation processes, such as unmanaged stratifications and lack of maintenance. This kind of situation are widespread in the several historical city centres of the whole Italy and, after the dramatic impacts of the most recent earthquakes, such as the 2016 Central Italy earthquake, we have witnessed an increased public awareness of seismic hazards that has highlighted the requirement of preventive measures to preserve the architectural heritage and to boost the resilience of regions prone to earthquake.

Moving from these suggestions, the main purpose of the current deliverable within the BE S2ECURE research project is to provide a definition of a seismic risk matrix considering all elements of the building stock which can affect open space in historical centre with the aim of envisaging damage scenario and assessing the BE seismic risk of the case studies presented in the previous D1.1.2.

The flow diagram (Figure 1) summarizes the structure and methodology followed: the current deliverable is focused on the review of the main topics (hazard, exposure and vulnerability) describing the seismic risk in order to find reliable assessment methodologies for each of them, with the aim of providing effective risk management models; the final paragraph is, in fact, focused on the development of a seismic matrix that encompasses all the parameters discussed.

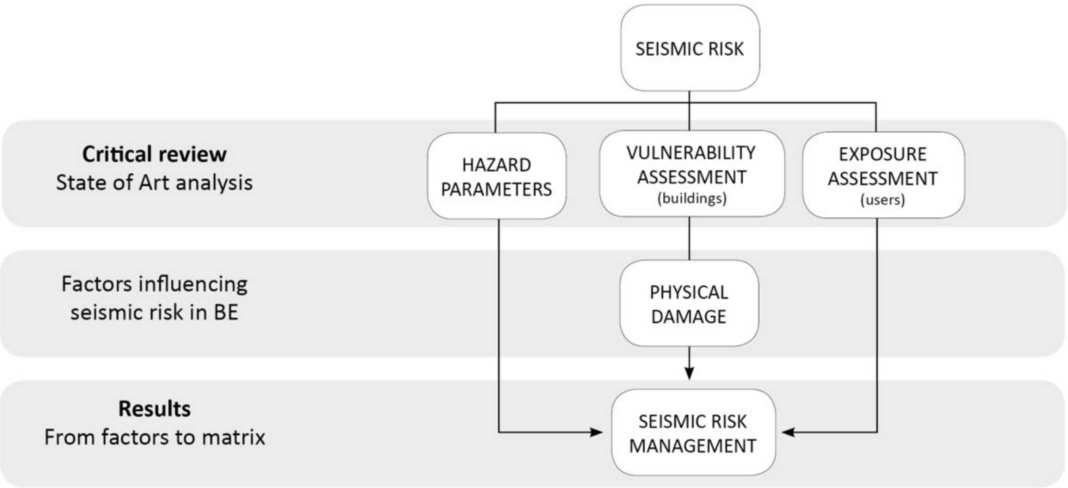


*Figure 1: Flow diagram of main issues debated about seismic risk within the current deliverable*

## 2. The seismic risk analysis

The concept of seismic risk was introduced during the international convention in 1979 organized by the Office of United Nations Disaster Relief Coordinator (UNDRO 1980). The equation below shows the most common way used to explain the concept of the seismic risk as the result of the combination of three elements: hazard, exposure and vulnerability.

$$R = H \times E \times V$$

The results provided by a seismic risk analysis encompass a great number of topics, nonetheless, its common use is aimed at evaluating the expected losses of an element at risk from a given hazard over a future period (Bendimerad 2001; Coburn and Spence 2003). This means that the seismic risk analysis is the estimation and the hypothetical, quantitative description of the consequences of seismic events upon a geographical area (a city, a region, a state or a nation) in a certain period of time. The effects to be predicted are various, from the physical damage to buildings and other facilities, to the potential economic losses due to the direct cost of damage and to indirect economic impacts (loss of the productive capacity and business interruption), or the loss of function in lifelines and critical facilities (such as hospital, fire stations, communication system, transportation networks, water supply, etc.) and also social, organizational and institutional impact.

The three parameters are affected by uncertainties of aleatory nature, related to the spatial variability of the parameters involved in the assessment and epistemic, related to the limited capacity of the models used to capture all aspects of the seismic behavior of buildings and of describing them in simple terms suitable for this type of analysis. Therefore, it should always be kept in mind that the computation of a risk level is highly probabilistic, and that to accurately represent the risk the expected values should always be accompanied by a measure of the associated dispersion.

In order to represent a useful tool for the purpose of the current research work, the seismic risk analysis will be thought and structured in such a way that consider the three elements composing the seismic risk to the context of historic city centres, especially referring to open space, which are the relevant topic presented in the previous D.1.1.1 and D1.1.2. The development of this D1.2.1 is represented by the topics outlined in red (Figure 2) but the main relevance will be given at the seismic vulnerability of historic masonry buildings and their assessment methodologies available in literature, with the aim of find the most suitable procedure that may lead to the estimation of the physical damages, which will be discussed in the D1.2.2.

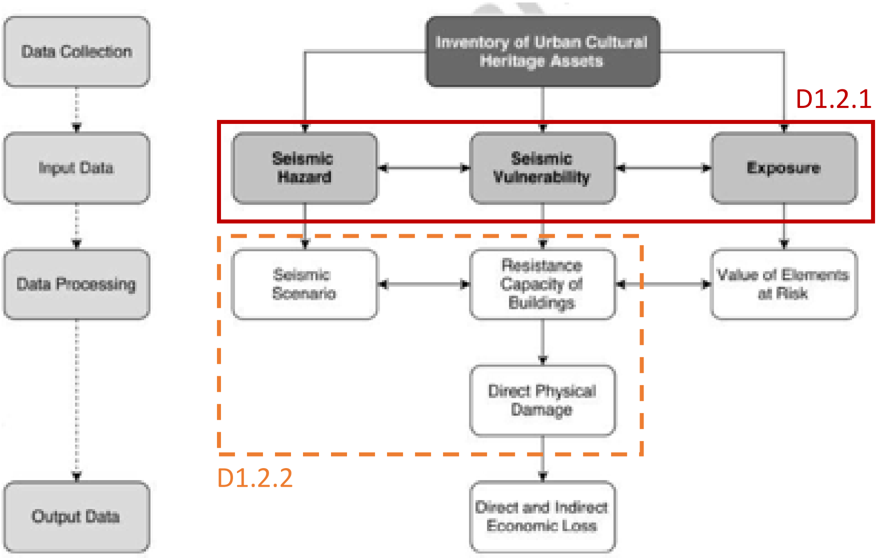


*Figure 2: Flow diagram with the steps for the assessment of earthquake risk* (Maio et al. 2018)

## 3. Hazard

The Seismic Hazard H is defined as the probability of occurrence of an earthquake of a certain severity, within a specific period of time, at a given geographical area (Coburn and Spence 2003). A seismic hazard analysis is aimed at describing the severity of ground motion and the measurement of earthquakes by appropriate parameters and it is basically related to the definition of damage scenario. The choice of the parameter to be employed for the ground motion characterization depends on the purpose of the risk analysis performed and must be coherent with the vulnerability assessment method adopted for the seismic building behaviour assessment.

The ground motion severity description may be specified in terms of its source characteristics, by magnitude, or in terms of its site characteristics, expressed by intensity, or by engineering parameters, such as peak ground acceleration (PGA) and spectral response.

- The magnitude of an earthquake is an objective, quantitative measurement of its total size, the energy released at its source as estimated from instrumental observations. It is widely described by the Richter Local Magnitude ML scale (Richter 1935).

- The intensity of an earthquake is a measure of the severity of the ground shaking on the basis of observed effects in a limited area (Grünthal 1998). The most natural parameter for the hazard description is the Macroseismic Intensity that is a qualitative description of the effects of the earthquake at a particular location, as evidenced by observed damage on the natural and built environment and by the human and animal reactions at that location and it has been evolving through the course of this century (Kramer 1996). Different Macroseismic Intensity Scale definitions are employed all over the world, which will be described in detail in D.1.2.2.

- PGA and response spectra are physical-mechanical parameters that describe the amplitude, the frequency and the duration of strong ground motion; the response spectra may encompass all of these characteristics while PGA only one.

However, the peak horizontal acceleration (PHA) known as peak ground acceleration (PGA) is the most commonly used measure of the amplitude of a particular ground motion and it represents the maximum value of the acceleration of the ground itself reached at any instant during the ground motion (Coburn and Spence 2003). Instead, the response spectrum describes the maximum response of a single-degree-of-freedom (SDOF) system to a particular input motion as a function of the natural frequency (or natural period) and damping ratio of the SDOF (Giovinazzi 2005). The response may be expressed in terms of acceleration, velocity, displacement and their maximum values are referred to respectively as spectral acceleration ($S_a$), spectral velocity ($S_v$) and spectral displacement ($S_d$).

### 3.1 The territorial seismic classification

Therefore, in recent years, several national codes have been equipped with hazard assessment models in order to provide a seismic classification of the territory. Hazard assessment may be deterministic or probabilistic, the first one is based on the study of observed damage of the past events at a given site, to determine the frequency of events of the same intensity; the second one, generally preferred, expresses the probability of an event with certain characteristics (in terms of PGA) occurring in a given return period. It entails mapping the whole national territory by the identification of genetic seismic zones and the quantification of their level of seismic activity.

Up to 2003 the Italian government has concentrated its action on the territorial seismic classification in tree seismic categories, each of which zone characterized by a value of the seismic action useful for the mandatory antiseismic planning, expressed in terms of maximum acceleration in rock. Thanks to further scientific development and studies carried out during INGV-DPC project (Meletti and Montaldo 2007), in 2006 was adopted an update of the code that introduces intervals of acceleration (ag), with a probability of exceeding the threshold equal to 10% in 50 years (SLV limit state), to be assigned to the 4 seismic areas (Table 1).

| **Seismic zone** | **Acceleration with probability of exceeding equal to 10% in 50 years (ag)** | |
|---|---|---|
| 1 | PGA > 0,25 | It the most dangerous area, where major earthquakes may occur. |
| 2 | 0,15 < PGA ≤ 0,25 | Municipalities in this area may be affected by quite strong earthquakes. |
| 3 | 0,05 < PGA ≤ 0,15 | Municipalities in this area may be subject to modest shocks. |
| 4 | PGA ≤ 0,05 | It is the least dangerous. Municipalities of this area have a low probability of seismic damages. |

*Table 1: Division of the seismic areas according to the acceleration of peak on rigid ground (OPCM 3519/06)*

### 3.2 The seismic microzonation (SM)

Local site conditions and irregular surface topography can substantially influence the amplitude, the frequency content and the duration of a strong ground motion and consequently can influence on the severity of the damage caused by the earthquake. Moreover, after an earthquake, the observation of damages on buildings often highlights substantial differences in different built-up areas, even lying at great distance from the epicenter. the possible causes are linked definitely to the quality of buildings, but often, also the local seismicity determined due to the different earthquake propagation, or the instability of the soil. While the seismic zonation provides basic hazard information for seismic classification, detailed considerations of geological characteristics of resistance and soil stability are part of the studies of Seismic Microzonation (SM). It is carried out at municipal scale in order to characterize: (i) stable areas, (ii) stable areas susceptible to local amplification, related to the lithostratigraphic and morphological characteristics of the area and (iii) areas subject to phenomena of instability and permanent deformation activated by the earthquake, such as landslides, surface fractures and soil liquefaction.

The Seismic Microzonation (SM) study has different level of detail which depends on the level of knowledge to achieve and its usefulness for the purpose, so as relating to the costs.

- Level 1 is a preliminary level, as it consists of a collection and interpretation of pre-existing data, such as available geotechnical parameters of near-surface formations by geological map, with the aim of subdividing the territory into qualitatively homogeneous microzones;
- Level 2 introduces the quantitative element associated with homogeneous zones and defines a true MS map, using investigations on the subsoil obtained by geotechnical survey instruments;
- Level 3 provides in-depth information on particular themes or areas aiming at solving uncertainties about particular ground conditions or wherein is evidence of recent instability. Since the 2016 earthquake a lot of municipalities have elaborated also the III level microzonation.

Microzoning maps are used by local authority and by urban planners to assist in earthquake protection in a variety of ways, offering useful information for both ordinary and emergency planning. As suggested by the Italian department of civil protection (DCP) the main applications of the SM studies may be: (i) orienting the choice of areas for new settlements, (ii) define the eligible operations in a given area, (iv) establish guidelines and methods of intervention in urbanized areas, (v) define priorities for emergency planning, e.g. choosing the location of strategic buildings or areas for temporary housing solutions.

The improvement of the knowledge produced by MS studies can concretely contribute together with vulnerability and exposure studies to mitigate and reduce the seismic risk. With this regard, the seismic microzonation information can be applied for the purpose of the current research to determine possible earthquake effects of the soil of areas selected as case studies.

### 3.3 Seismic classification map, database and further development of hazard models for the Italian territory

The map provide the distribution of the seismic zones from 1 to 4 within the entire Italian territory divided into municipalities or provinces (Appendix 10.1). It is developed at the regional scale through the SM studies conducted by municipalities and then all the information are updated at national scale and collected into the seismic classification map shared online by DCP.

Another tool providing useful information to adopt for SM studies, is the Database of Individual Seismogenic Sources (DISS 2018), that is a repository of geologic, tectonic, and active fault data for the entire Italian territory. Overall, it contains 127 Individual Seismogenic Sources, 188 Composite Seismogenic Sources, 35 Debated Seismogenic Sources, and three subduction zones. All seismogenic sources and areas are based on geological/geophysical data characterized by a full set of geometric (strike, dip, length, width and depth), kinematic (rake), and seismological parameters (single event displacement, magnitude, slip rate, recurrence interval) that describe sources three-dimensionally. This database contains all the information modelled in agreement with the previous seismogenic zones (SZs) maps [ZS4 by (Meletti et al. 2000) and ZS9 by (Meletti et al. 2008)] used for the Italian seismic hazard maps. This version of the DISS is updated due to the availability of new data and studies that highlighted the possibility of a better definition of the potentially SZs (Santulin et al. 2017). So that, the database contributes to the new national seismic hazard model for Italy in the framework of MPS16 Project.

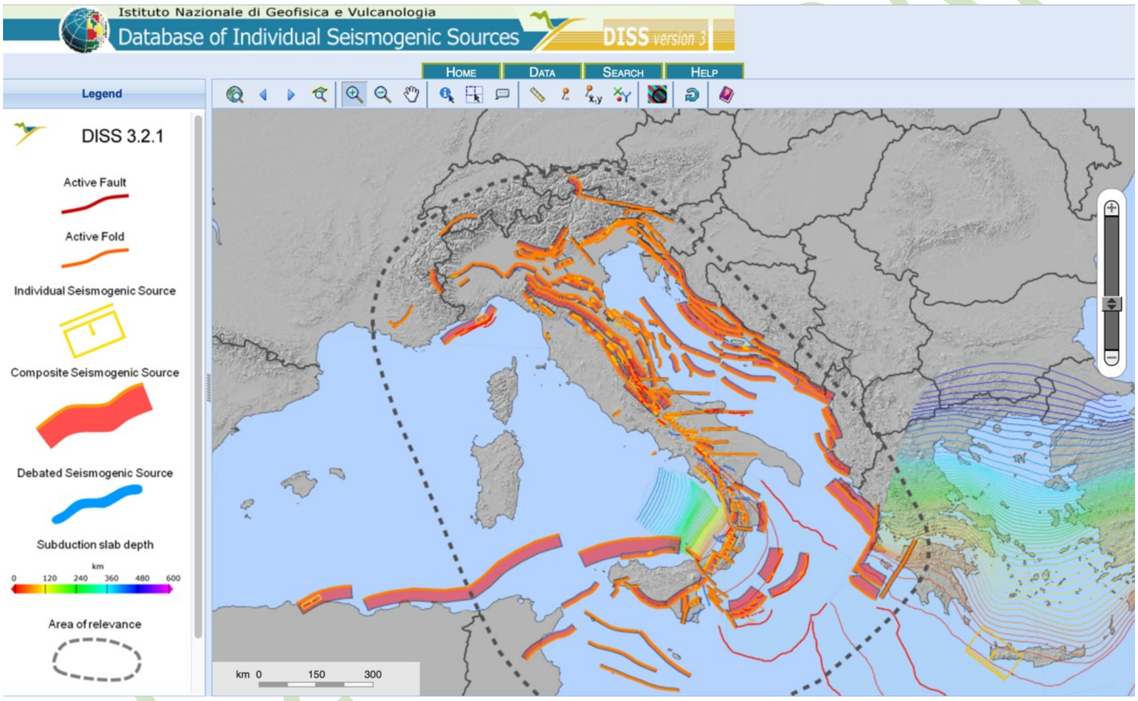


*Figure 3: The DISS database available online at http://diss.rm.ingv.it/dissmap/dissmap.phtml*

In fact, in 2015 the Seismic Hazard Centre (Centro Pericolosità Sismica - CPS) of the National Institute of Geophysics and Volcanology (INGV) was commissioned to coordinate the national scientific community with the aim of elaborating a new reference seismic hazard model (Meletti et al. 2019). The purpose of the MPS16 project came from the need of updating the hazard maps (Figure 30) performed by the MPS04 model (Meletti and Montaldo 2007), which will be briefly discussed in §7.1. These maps will be indeed replaced by the new probabilistic seismic hazard model of Italy, named MPS19, that will be probably released by the end of 2020. One of the tasks of MPS19 (Lanzano et al. 2020) is focused on the prediction models for strong motion parameters, named Ground Motion Models (GMMs), and for macroseismic intensity to be used for the selection of models in the framework of PSHA (Probabilistic Seismic Hazard Assessment).

## 4. Exposure

The exposure is typically defined in literature as the situation of people, infrastructure, housing, production capacities and other tangible anthropic elements located in hazard-prone areas (UNISDR 2009). Furthermore, many authors provide a description of exposure connecting to the potential losses of the elements at risk (people, property, systems) under natural disaster, referring to the economic impacts of commercial and technological assets under earthquake (Coburn and Spence 2003). The first definition describes exposure in terms of quantity, which considers the location and distribution of the elements at risk, and the second one in terms of quality, considering the functional or strategic value and the relationship between physical elements and territorial system.

Moreover, Cremonini (1998) has distinguished two different definitions: the physical exposure of elements whose conditions can be damaged or destroyed causing economic loss, and, the systemic exposure, when the loss of the element exposed affects the performance of the whole urban centre by the interaction of the component's functions. Also other authors (Dolce et al. 1994) encompass in the definition the people, property, cultural values, activities that may be adversely affected during an earthquake in relation to the performance of a built system. According to Fera (1991), the exposure determines the distribution and value of the assets (population, economic and public activities) constituting the building stock that could be affected by seismic events. Following the same approach, Venco (Venco 2016; De Lotto et al. 2019) considers two different dimensions of exposure, the physical (amount of goods or persons exposed) and the functional (strategic, economic, historical-cultural role), and then, three macro-categories of elements potentially exposed, the population (resident and city users), the physical elements (residential, cultural, strategic buildings, mobility assets) and the economic activities (productive and industrial).

So that, an exposure analysis should highlight the number and the quality of the elements exposed that have to be characterised by different indicators due to the type and the aim of the investigation. The heterogeneity of the required data imposes the definition of a systematic method that involves indicators and parameters that may synthetically summarize all the exposure conditions of a specific territory.

The exposure estimates in quantitative terms the possible economics and social effects of a natural disaster by combining different parameters, as population density with the presence or cultural heritage or strategic assets in a hazard prone area. Moreover, in urban areas the exponential growth of population and its density makes cities more exposed to the impact of natural disaster. In fact, unplanned urbanization, urban sprawling, sudden demographic changes have considerably contributed to modifying the type and spatial distribution of exposure, and hence, the expected risk (Aubrecht et al. 2013). So that, the exposure assessment has a key rule for implementing risk reduction strategies, although their successful applications require in deep knowledge of the area under investigation and detailed analysis of its urban assets and exposed elements. Researchers generally model exposure as a minor input for risk assessment, so that has led to an underrepresentation and a lack of understanding of the relevant contribution of exposure to reducing seismic risk. Therefore, detailed discussions of the exposure modelling process are very limited and almost absent in the literature (Rivera et al. 2020).

### 4.1 Human exposure prone to earthquake

Recently, the seismic risk assessment approaches have changed by the integration of contributions to psychological science about human vulnerability aspects in order to consider not only technical and engineering issues in urban environmental risk management but also social aspects (Pelling 2003; UNDRR 2015).

Within the risk assessment models, the potential human and physical exposure have generally been estimated per each hazard separately and then aggregated at country level. The human exposure is based on the estimated number of people exposed to a given hazard. It results from overlapping of the hazard zones and the total population living in the spatial unit. Similarly, the physical exposure is based on the estimated total built-up surface exposed to a given hazard. It results from the combination of the hazard zones and the total built-up surface in the spatial unit and it thus indicates the expected number of built-up surfaces exposed in the hazard zone.

The concept of human exposure could seem too vague because it encompasses several areas of natural disaster risk; so that, it is worth clarifying that in the following parts we will deal with human exposure only referring to seismic risk, with the purpose of identifying assessment methodologies aiming at recognizing both permanent (i.e. resident) and temporary (i.e. city users, workers, students) presence of people prone to hazard.

### 4.2 Human exposure assessment approaches

For all these reasons, assessing exposure relies on several steps aiming at ensuring a uniform interpretation of data: the definition of the investigation scale and context due to the specific results required by the risk analysis, the identification and classification of the element at risk under investigation by creating the corresponding taxonomy, the definition of synthetic parameters and indicators. Among these steps, the choice of the information for computing indicators and the data source are fundamental to achieve complete and effective exposure scenarios. A unified and flexible description of exposure is still missing in literature, although several structural taxonomies have been developed in order to classify and characterize buildings, there is a lack of relevant data describing the parameters of use, occupancy and dynamics factors. Throughout this insight, we provide a brief state of art of main parameters and indicators used for housing stock inventories and also, we will focus on human exposure, which is an essential component when considering behavioural model in risk and emergency management.

Different ways are developed to address exposure in the seismic risk assessment depending on the type of data required for achieving the results and the detail level of the collected data which may substantially varies between global or local analysis. The wider approach relies on the collection of data that describes specific features of the element at risk in terms of numerical indicators or qualitative classification. For instance, the elaboration of crowding index quickly identifies the occupancy of building or territory, but it requires detailed information to be computed and it is not suitable to large scale evaluation.

Therefore, some approaches have adopted aggregation data and macroscopic indicator to represent the exposure more quickly. Authors (Chen et al. 1997) have proposed an exposure analysis by employing as a macroscopic indicator the Gross Domestic Product (GDP) to represent social wealth and to estimate earthquake loss. The fundamental assumption of this holistic technique is that the number of anthropic facilities is directly proportional to social wealth, and it could be a useful tool giving quick risk information (due to the limited inventory data required) in earthquake loss estimation at national or global scale.

Exposure is indeed commonly treated as being constant in time, but this approach neglects the dynamics associated with rapid urban transformation and urbanization, misrepresenting the real risk condition of a territory. From this point of view, recently some authors (Rivera et al. 2020) have developed a novel approach according to the temporal dimension of the seismic risk assessment, in fact they proposed an interdisciplinary study to understand the spatiotemporal dynamics of seismic exposure in Santiago de Chile by quantifying the urbanization changes over the time. The results demonstrate the role of seismic risk awareness as drivers for urban development policy, so that, nowadays exposure model provide useful tools in DDR strategies.

Exposure techniques have been developed to describe the distribution of multiple types of exposure at various geographic scales, from global to local, thus it is possible outline three main aspects that heavily influence the modelling process and its results:

- **Global scale models** have a "top-down" approach since the investigations are carried out by government or large institutions by adopting census data, global databases, and remote sensing at national level or above.
- **Local scale models** work from the "bottom-up" by using crowdsourcing methods, in situ surveys and aerial photos, or, GIS data and economic reports at a regional and provincial level.
- **Dynamic exposure models** are composed by a database able to track the element's evolution over space and time in order to consider the time dependency of exposed assets as a component that greatly affects the risk assessment. Aubrecht (2013) emphasize the importance of capturing the dynamics by which exposure evolves over time because it would be useful, not only, for regions that are experiencing rapid social and economic change (GFDRR 2014), but also for urban area wherein human exposure is strictly dependent on daytime users and mobility flow. With this regard, it is therefore appropriate to distinguish the long-term (years) variation considering large scale exposure assessment, between the short-term (daily and weekly) variations at the local scale referring to the temporal change in the occupancy of buildings due to patterns of social mobility (service users, students, workers). This latter temporal variation can strongly affect the quantification of human exposure in cases of sudden-onset disasters, and hence these changes should be recorded in exposure models that need to be constantly updated in order to avoid obsoleteness of information and inefficiency in exposure assessing.

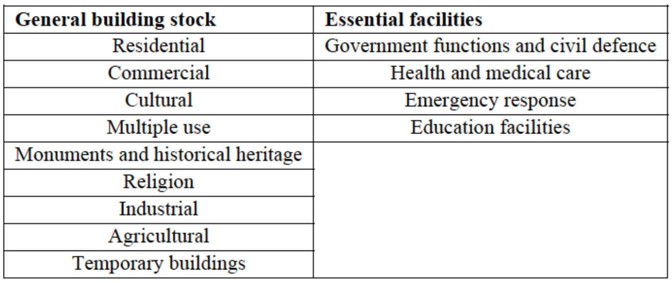
The tools and methods for defining exposure need to consider the dynamic nature of human settlements but recording and computing these changes and trends is very complex due the interdependent of spatial and temporal dimensions: human settlements, where people live, work, and move, experience variations that census and administrative geographical unit definitions often are unable to depict.

### a. Taxonomies and indicators for describing the BE exposure

The building exposure models is important not only to help to estimate the damage to buildings and losses, but also help to understand the impact of seismic event on people's lives. Nowadays, numerous methods available for assessing earthquake exposure of buildings but these are especially focused on the description of the structural typologies of the buildings stock. In fact, these classifications have been developed and are widely used in the world and in Europe for large-scale assessments and their main purpose is to assign damage state to particular buildings, and hence, to evaluate the economic impact of earthquake (Pavić et al. 2020). These approaches return a partial framework of seismic effects and are only aimed at the estimation of the cost of the reconstruction phase. With this regards, the most common structural classification systems are adopted by ATC13 (1987), HAZUS (1999) and EMS-98 (Grünthal 1998). Most of these have a regional or a country-based focus, and the only two describing the global building stock are PAGER (Jaiswal and Wald 2008) and the WHE. The World Housing Encyclopedia (WHE) is an open-source database that includes the description of 110 housing types contributed by 180 volunteer engineers and architects from various countries and regions and it is often adopted by researcher to improving novel buildings inventories.

There are few classifications that also involve buildings characteristics that may quantify the exposure of population or people who lives and use the buildings. It is therefore necessary a classification system that takes into account the buildings occupancy, which is the type of activity (function) within the building (i.e. residential, commercial, industrial), in order to consider the number of users related to the buildings surface and other factors that cause casualties. The EMS-98 defined this aspect as "importance" of a building that is determined by the number of occupants or visitors, by the use of the building (or the consequences of interruption of the use) or by the danger for public and environment in the case of the building's failure. The Global Earthquake Model (GEM) has developed unambiguous building taxonomy that summarizes several information including the occupancy as shown in Appendix 10.2.

In addition, the Figure 4 shows general occupancy classes both for general building stock and essential facilities according to the classification proposed in the framework of Risk-UE project-WP1 (Lungu et al. 2001).



| General building stock | Essential facilities |
|---|---|
| Residential | Government functions and civil defence |
| Commercial | Health and medical care |
| Cultural | Emergency response |
| Multiple use | Education facilities |
| Monuments and historical heritage | |
| Religion | |
| Industrial | |
| Agricultural | |
| Temporary buildings | |

*Figure 4: Occupancy classes for general building stock and for essential facilities* (Lungu et al. 2001)

A relevant support to the data collection is also given by PAGER (Prompt Assessment of Global Earthquakes for Response), the building-specific inventory developed for the casualty estimation methodology used for the U.S. Geological Survey's, provides occupancy-specific information compiling data from various sources and allows to determine the average occupancy during day and night time of each building class. In fact, the PAGER inventory is generally categorized in terms of residential, nonresidential or outside and the database provides information about the fraction of people in each of these three occupancy categories. For example, into the nonresidential category were classified the fraction of people working in various types of facilities (such as administrative, commercial, banks, academia), while, people residing in single or multi-family dwellings could be grouped into the residential category, and the fraction of the population that does not belong to either type is termed as outside. In the absence of such specific categorization, are used to convert the raw data into the equivalent three occupancy categories. Since most of the databases provide only residential building stock data and do not have occupancy defined as a function of the time of day, it is necessary to correct the information separately to each occupancy category by using engineering judgment. For instance, estimating fraction of occupants living in the residential dwellings is available due to the residential building inventory database of any countries, but not the exact fraction of the population living outside, so, the algorithm calculate the total work force (labor force) in each country and then assign the fraction of people not residing in residential dwelling during work hours. The average number of occupants in a particular building type is derived from the WHE database (EERI 2007) and the ATC procedure and it is summarized in Appendix 10.3.

These latter approaches demonstrate that generally seismic risk analysis proposes an exposure definition in terms of population density obtaining by census data although this proceeding has some limitations. In fact, according to the said above, the population is defined only as permanent resident population of residential buildings, not considering specifically the variation of people distribution due to the use of specific facilities or commercial buildings existing in a territory. As previously claimed, the exposure is time-dependent especially in metropolitan areas due to human activities and mobility that greatly varies the spatial distribution and density of population between day and night (Freire 2010). Therefore, a more accurate assessment of population exposure and risk analysis requires going beyond residence-based census data and figures the accurate quantification of users depending on buildings function and their time utilization in order to be prepared for events that can occur any time and day. Identifying distinct daytime and nighttime population distribution characteristics on local scale is the major challenge for human exposure models compared with standard census-based models, but there are still few works developed in this direction.

One traditional way to describe the spatio-temporal patterns of human exposure is defining synthetic indicators that calculate the people distribution relating to specific building function. In order to quantify this information, for first, it is important to establish the scale of the investigation and the detail level of the expected results. For example, the use of territorial indicators is always a valid support to the municipalities planning for evaluating strategies of urban interventions. The indicators aggregation processes rely on dataset from municipalities reports, expert judgment or on-site survey, which is further collected in GIS tools (Geographic information system). For instance, the correlation between the built-up surface and the related number of users provides the crowding index that may be referred to the building occupancy and to the usage time. As previously shown, there are few references in literature providing this type of indices and often they are related to buildings standards and construction codes. As suggested by Venco (2016), within the Italian regulation framework, the guideline UNI 10339:1995 establishes the thermal comfort requirements in buildings and hence provides a list of crowding indices related to the typical values for building occupancy (Appendix 10.4). The regulation outlines that such indexes are to be considered as reference to design assumption, with respect to the indoor air quality, about typical values of human occupancy, whereas specific information of real data are not available. However, if no values are declared, the default values given in Appendix 10.4 shall be applied. In fact, even though it is referred to technical installations, it provides detailed measures of crowding index for each case of buildings function that, otherwise do not be available in other regulation, and they will be useful also for our purpose. In addition to this standard, another useful reference to crowding threshold is provided by the Italian Fire Prevention Code (FPC) (DM 3/08/2015). In fact, it contains the best fire provision to mitigate and reduce the fire risk to an acceptable level. Among these, a list of crowding index or criteria for the maximum crowding allowed (Appendix 10.5) is provided for several activities that are subjected to fire prevention inspection. Each of the standards may be adopted as reference of average or maximum value of crowding, wherever specific design data are missing.

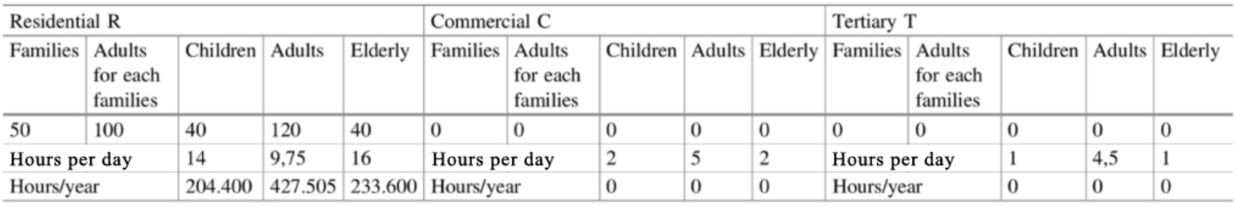
An application of this approach has been proposed by De Lotto et al. (2019) wherein the exposure model takes into account number and type of users (children, adults, elderly), urban building functions (residential, commercial, tertiary), the related crowding index (50 $m^2$/person for the residential, 0.25 persons/$m^2$ for the commercial and 0.1 persons/$m^2$ for the tertiary) and the time-dependent distribution.

Then, the exposure function has been calculated as shown by equation (1) and (2) (translated and rewritten), and hence has been analyzed to determine the best possible combinations of urban function and population distribution (Figure 5, Figure 6) in order to planning scenario aimed at reducing the exposure level.

$$E_{TOT} = \sum E_{u.f} \tag{1}$$

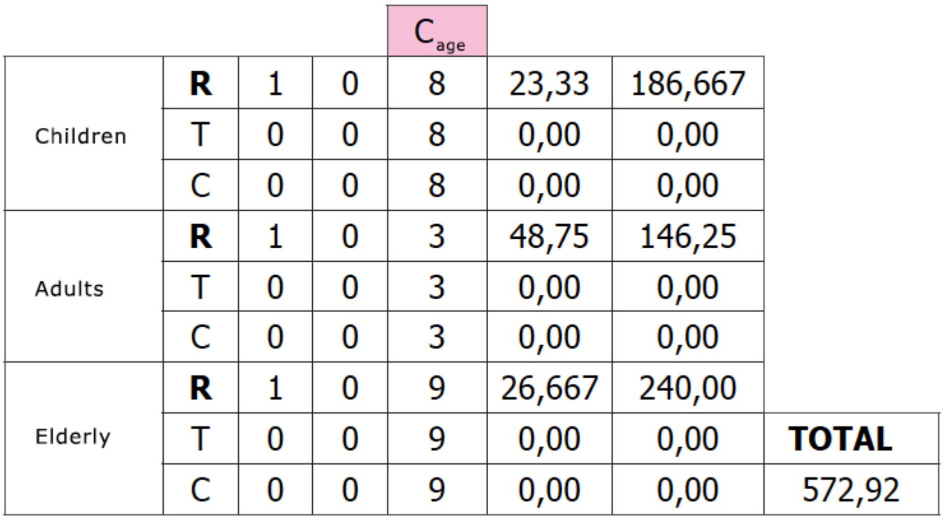
$$E_{u.f} = \sum\nolimits_{age} \left( \frac{\frac{m^2 \, u.f.}{d}}{persons} \right) \times \left( \frac{m^2 \, u.f.}{m^2 \, tot} \right) \times \left( C_{age} \right) \times \left( \frac{hours}{hours \; a \; year} \right) \tag{2}$$

*u. f. = urban function*
*d = population density for each urban function calculated by index crowding*
*persons = total population of the urban block*
$C_{age}$ *= corrective ratio corresponding to people's age and to the related movement skills*



| Residential R | | | | | Commercial C | | | | | Tertiary T | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Families | Adults for each families | Children | Adults | Elderly | Families | Adults for each families | Children | Adults | Elderly | Families | Adults for each families | Children | Adults | Elderly |
| 50 | 100 | 40 | 120 | 40 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Hours per day | | 14 | 9,75 | 16 | Hours per day | | 2 | 5 | 2 | Hours per day | | 1 | 4,5 | 1 |
| Hours/year | | 204.400 | 427.505 | 233.600 | Hours/year | | 0 | 0 | 0 | Hours/year | | 0 | 0 | 0 |

*Figure 5: Urban functions and time of use per group of people (De Lotto et al. 2019)*



| | | | | $C_{age}$ | | | |
|---|---|---|---|---|---|---|---|
| Children | **R** | 1 | 0 | 8 | 23,33 | 186,667 | |
| | T | 0 | 0 | 8 | 0,00 | 0,00 | |
| | C | 0 | 0 | 8 | 0,00 | 0,00 | |
| Adults | **R** | 1 | 0 | 3 | 48,75 | 146,25 | |
| | T | 0 | 0 | 3 | 0,00 | 0,00 | |
| | C | 0 | 0 | 3 | 0,00 | 0,00 | |
| Elderly | **R** | 1 | 0 | 9 | 26,667 | 240,00 | |
| | T | 0 | 0 | 9 | 0,00 | 0,00 | **TOTAL** |
| | C | 0 | 0 | 9 | 0,00 | 0,00 | 572,92 |

*Figure 6: Calculation of the ETOT in case of the 100% of residential urban function (Venco 2016)*

The current work considers most of parameters required to describe the human exposure outlining the difference between user's age groups and between distribution of different urban functions expressed by crowding index. Even though this approach requires a detailed knowledge of the urban context because it is essentially based on assumptions by on site survey, expert judgments, local census data or standards, it still remains the most commonly adopted and easy to use.

### b. Further technological development: multi-level approaches on real-time population distribution

Nevertheless, looking at further advances in this field, new technologies may represent the driver to improve data storage and processing capabilities allows moving toward real-time representation of human movement (Aubrecht et al. 2011, 2012). As previously claimed, the real-time distribution of people during the day to the different urban functions and the relative occupancy of the buildings play a key role in determining the level exposure of an urban area; the possibility to easily obtain these information and achieve a high level of data reliability is hence the next challenge of studies in this field. The quality of available input data in terms of both spatial and thematic accuracy influences the reliability of the overall risk assessment. For example, census data are widely available, but nonetheless, in inhomogeneous spatial reference units for assessing both large and local scale. Therefore, the use of satellite data, Big Data, social applications georeferenced or Wi-fi tools, may lead to a great reliability of the assessment results and therefore the effectiveness of the DDR strategies.

For this purpose, mapping cellular phone user activity may be a powerful tool to record time-specific population distribution and location (Loibl and Peters-Anders 2012). Thus, the population number at a certain time in a certain area can be examined and in a further step, the potential time-specific human exposure to a dangerous situation or hazard evaluated. An attempt within this approach has been developed by authors (Lu et al. 2013; Wesolowski et al. 2013) to derive mobility patterns.

Another way for analyzing population dynamics and deriving is opening up with the availability of location-specific volunteered geographic information (VGI) drawing upon the increasing number of persons who are equipped with ‘‘location sensors’’ in the form of GPS-enabled mobile devices (Goodchild and Glennon 2010). The willingness to share the personal location with others is generally increasing rapidly and is facilitated by rising new technologies tools used within the social networks.

The Global Human Settlement Layer (GHSL) project, supported by European Commission-Joint Research Center, produces new global spatial information on built-up surface and population that have been combined with geospatial datasets with the aim of assessing the human and physical exposure potentially affected by i) environmental contamination and degradation, natural disasters and conflicts, ii) impact of human activities on ecosystems, and iii) access to resources. The methodology relies on the design and implementation of new spatial data technologies allowing to process and extract analytics and knowledge from large amount of heterogeneous data including global, fine-scale satellite image data streams, census data, and crowd sources or volunteering geographic information sources. The spatial raster dataset, which forms the built-up surface density map, has been overlaid with residential population data estimated for target years 1975, 1990, 2000 and 2015 and then were disaggregated from census or administrative information to grid cells.

CEGIS researchers have tested the application of volunteered geographic information (VGI), which is geospatial content generated by non-professionals using mapping systems available on the Internet, with the aim of enhancing the geospatial databases of government agencies. They hence analyzed the accuracy of data produced by volunteers on structures (schools, hospitals, etc.) to incorporate into the official databases that comprise The National Map. Results have shown that some participatory mapping projects can produce data that are as accurate as those produced by these agencies, because contributors have unique local knowledge. Another application for hazards science projects at the USGS (United States Geological Survey) is to investigate the opportunities and challenges with integrating official and crowdsourced geospatial data around hazards, not only for scientific research but also for operational purposes in emergency management and risk reduction. In fact, after a crisis event, different communities will use online mapping and social media such (Twitter, Facebook) to communicate information about the event, such as hurricanes and earthquakes. Crowdsourcing the analysis of aerial images has the potential to improve models of environmental changes and disaster domain.

Another tool recently developed is the LandScan Global dataset (Oak Ridge National Laboratory), a high resolution spatio-temporal global population distribution dataset (1-km raster) that may contain both nighttime residential and daytime population distribution information incorporating movement of workers and students. The algorithm processes geospatial data (including land cover, roads, slope, urban areas, village locations), high resolution imagery analysis technologies and a multi-variable dasymetric modeling approach to disaggregate census count aiming at mapping population distribution. Within each country, the population distribution model is weighted for each map cell as the possible occurrence of population during a day by providing a "likelihood" coefficient. Then, the coefficient has been applied to the census counts in order to consider also socioeconomic and cultural understanding of an area for calibrating the distribution model. Finally, the total population obtained is an average day/night population count and it is allocated to each cell proportionally to the calculated population coefficient.

The application of these real-time data could definitely provide useful information for accurately estimating population exposure, even though it has some limitation and overall accuracy remains an issue of debate. Indeed, it requires huge computational efforts to overlay all input data between official census data and population density and especially continuous updating.

### 4.3 Further developments of human exposure assessment of BE on open space

After the latter state of art, it is necessary to choose the line for the exposure assessment of the current research. As previously outlined, are different point of view in this field and the first step for defining exposure model is the choice of the elements that must be studied and the relative parameters which affect the overall aim of the analysis. The exposure concept more suitable with the main purpose of the current research takes in account the definition not in terms of human exposure considering the interaction with the BE and the OS. In fact, urban areas are characterized by high interference level between the surrounding buildings and the potentially high population densities, including tourists who can be unfamiliar with the environment. So that, it is very important to provide a correct number of people distinguishing between inhabitants and other users related to buildings function in order to verify the level of crowding. On the other hands, also the time and the frequency of the buildings usage by people have been defined considering the distribution variations during daytime and during the year. Human exposure is strictly related to social domains, such as the vulnerability of age groups or disabled population, so that also these parameters have to be addressed as eventually influencing the people preparedness for earthquake scenarios.

Summarizing these latter parameters into synthetic indicators is the purpose of the open space exposure assessment suggested for the case studies involved in the seismic risk evaluation of the BE S2ECURE project. The exposure distribution is calculated as shown by the equations (3) and (4). This function takes into account several parameters, which are detailed explained below, and the computing procedure is summarized in the Table 2.

$$Exposure = \mathrm{E}_{\mathrm{BE}} + \mathrm{E}_{\mathrm{OS}} = \sum E_{BFU} + \mathrm{Eos} \qquad (3)$$

$$E_{BE} = \sum U_{BFU} \cdot h_d + \sum U_{BFU} \cdot (h_n \cdot C_n) + \sum U_{BFU} \cdot (h_h \cdot C_h) \qquad (4)$$

where $U = m^2{}_{BFU} \times CI$

- BFU: Buildings Functional Use ($m^2$), corresponding to the functions and use proposed in the form used for checking the case studies in D1.1.2.
- CI: Crowding index (persons/$m^2$) enables to quantify the number of occupants or visitors per building functions. It is based on the UNI 10339 (Appendix 10.4) and the FPC (Appendix 10.5) standard; these values are used as reference in absence of certain real data.
- U: Users, divided into Adult (A), such as people of 18 – 65 years, Children (C) under 18 and Elderly (E) over 65. Children and elderly persons are considered “vulnerable” age class, with this regard corrective coefficients $C_C$ (1.6) and $C_E$ (1.8) have been added in the calculation. The number of adults, children and elderly corresponds to the percentage of the related age group within the population of the whole urban context. This information is usually available by local census data or municipality reports.

$$U_{BFU} = A + C' + E'$$

$$A = x_{\%A} \cdot U$$

$$C = x_{\%C} \cdot U$$

$$E = x_{\%E} \cdot U$$

$C' = (C \cdot C_C)$ where $C_C$= 1.6

$E' = (E \cdot C_E)$ where $C_E$= 1.8

- Occupancy consists of the occupancy time of buildings during the day (8am – 8 pm), night (8 pm – 8 am) and holidays. This parameter represents the temporal dimension of exposure and allows to quantify the number of people per building class; therefore, different emphasis has been given on night and holiday class through corrective ratio $C_n$ (1.5) and $C_h$ (1.2).

| BUILDING FUNCTIONAL USE | | CROWDING INDEX | USERS | | | TIME OCCUPANCY | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *($m^2$)* | *(persons/$m^2$)* | *A / C / E ($m^2$/ CI)* | | | *Daily time (h/12)* | | | *Night time (h/12)*$C_n$* | | | *Holidays (h/8760)*$C_h$* | | |
| Residential | | 0.04 – 0.05 | | | | | | | | | | | | |
| Commercial | | 0.1 – 0.20 | | | | | | | | | | | | |
| Strategic buildings | | 0.12 | | | | | | | | | | | | |
| Sights (archeological sites, museum, monuments) | | 0.3 – 1.2 | | | | | | | | | | | | |
| Theatre, cinema | | 1.5 | | | | | | | | | | | | |

*Table 2: Exposure classification of BE*

The final value obtained will be normalized from 0 to 100 and then divided into classes that form the matrix developed for assessing seismic risk as explained in §7.2.

## 5. Vulnerability of buildings

The term vulnerability has been debated by authors related to a wide range of approaches, sometimes contrasting definitions risk to be overlap and lead to misunderstandings of topics that must be dealt with in the assessment methods. So that, this section reviews some existing definitions available in the literature with a focus on buildings vulnerability under earthquake different approach with the aim of clarifying our position about that it will follows until defining of the suitable vulnerability assessment methodology.

The vulnerability was introduced as a response to the hazard perception of disasters in the 1970's and then was used to express the extent to which people suffer from calamities depends on (i) "the likelihood of being exposed to hazards" and (ii) "their capacity to withstand them, which relates to their socio-economic circumstances" (Dilley and Boudreau 2001).The first one may be overlapped with risk definition because it refers to the state to be at risk and to be affected by damage, the second one describes the intrinsic behaviour to withstand disaster. Subsequently, some authors have identified the vulnerability as the degree of loss to a given element at risk resulting from a given hazard (Buckle et al. 2001) or the proportion of buildings experiencing some particular level of damage (Coburn and Spence 2003). Another group of definitions emphasises rather the potential of loss due to an adverse response to events (Charlotte and J. 2006). It is worth clarifying the separation between risk and "innate risk" or "pure vulnerability" which emphasises the characteristics of the elements at risk. Some authors (Chambers 1989; Bohle 2001) propose a "social" definition of the vulnerability as the internal dimension refers to defenselessness and insecurity, the capacity to anticipate, cope with, resist, and recover from the impacts of a hazard. The external dimension involves exposure to risks and shocks. Although the latters argue the concept, which is nowadays widespread and well known with the term "resilience", whilst we concur with the distinction between internal and external dimensions.

For our purpose, we will translate these latter concepts to the built environment in order to find the most appropriate vulnerability definitions for the most suitable vulnerability assessment.

First of all, the seismic vulnerability is the intrinsic predisposition of a building to suffer damage from a seismic event of a given intensity. This concept is applied in the EMS-98 scale, even though this word was not explicitly used, building type was used as a simple analogue for vulnerability an easy way of approaching the problem of vulnerability. This means that each building class has an intrinsic predisposition to be vulnerable under earthquake due to the its construction characteristics and the own structural behaviour.

According to this approach, Doglioni (2000) distinguishes the vulnerability in (i) "specific", depending on the construction characteristics, such as the masonry quality and workmanship that Giuffrè (1990) calls "regola d'arte"; (ii) "typical", characterised by architectural peculiarities of each buildings typology (church, buildings aggregates, tower) that determine the mechanical behaviour under seismic events. The extrinsic vulnerability, otherwise, deals with the buildings facing streets to consider for the assessment and design of people's safety during earthquake emergency in the urban environment. The latter will be discussed in detail in the D131.

Move from these suggestions, the vulnerability assessment within the definition of seismic risk, assumes great importance, not only because of the obvious physical consequences in the eventual occurrence of a seismic event but also because it is considered by many authors as the most eager element to be mitigated. The vulnerability assessment depends on the latter parameters and the outcomes differ between the used input data and the specific purpose of the analysis. Each method leads to define the seismic response of the building stock in numerical term, but, as it is already outlined, also the assessment methods have been confused and overlapped with seismic risk analysis due to the definition of the vulnerability concept. With this regard, in the review presented below it will be clarified these misunderstanding, for instance, the damage probability matrix (DPM method) represents a vulnerability definition in terms of loss and expected damage, thus this should not be envisaged within the suitable methodologies.

Moreover, the vulnerability assessment varies according to the intent and the subject of the evaluation depending on both the wealth and the quality of the available data. In fact, the vulnerability method makes reference to a single building, a building typology and building or urban system, thus it is necessary to specify the micro-scala or macro-scala of the requiring analysis in order to obtain the best reliability of the results. This means that performing a study for different scale of analysis (local or territorial scale) it is not possible to operate with the same vulnerability method.

The final purpose of the current discussion is to highlights what is the impact of an earthquake on the BE, evaluating the physical damage of buildings facing aereal space by assessing their vulnerability and calculating the amount of debris could occlude the public space, road or open space. With this aim, a brief review of relevant international vulnerability methods is presented in the following paragraph, showing how the seismic input are employed. Then, the approaches will be compared, their effectiveness in assessing historic city centres will be highlighted and the main relevance pointed out in order to identify the approach that best predicts the seismic vulnerability and specific needs for developing a novel method.

## 5.1 SoA of vulnerability assessment methodologies

The present paragraph is aimed at discussing some of the concepts outlined in the previous parts through the discussion of the several methodologies developed in the past 30 years for assessing the seismic vulnerability of buildings. They follow distinct approaches based on different data sources in terms of qualitative or quantitative input of the procedure to define the vulnerability distribution. The choice of the most suitable procedure is highly dependent on the resources available for the data collection, the computational expertise available, and ultimately the scale and aim of the study, for instance, the large scale studies to define damage scenarios require different approach regarding studies aimed at identifying specific buildings in need of strengthening. Moreover, the different nature of the approach influences the type of protocol used and output obtained, from the expedite evaluation of buildings to more complex numerical modeling of single building.

It is worth reminded that the vulnerability definition which is the most suitable for our purpose is that encompasses the physical attributes of the building stock through the reconnaissance of all the critical construction features, which will be defined in detail in §5.2.

The following paragraphs report an overview of the main classification of vulnerability assessment methods reported in the literature (Calvi et al. 2006) classified in two approaches: empirical and analytical.

### a. Empirical methods

The empirical methods rely on the wealth of observed damage data available from past earthquake and the correlation of the performance of buildings to the seismic intensity of the occurred events. The aim of this procedure is to extract statistical functions that relate the probability of damage suffered by a building type, at a given site, to the expected shaking intensity.

The major limitation is the dependence on the ground motion of the observed seismic event on the specific architectural context. In fact, a large set of data and multiple observations of different type of building damage are necessary to produce functions valid at territorial scale for describing the performance of the common building typologies to the several possible seismic intensities. Depending on the availability of the collecting damage data, these methodologies are grouped into essentially three categories in terms of their level of detail, the scale of evaluation and use of data. For instance, approaches which use a considerable amount of qualitative data are ideal for the development of seismic vulnerability assessment for large scale analysis. On the other hand, mechanical models of the building scale, require a higher quality of information, as geometrical and constructive details regarding building stock. Although this is an observational method and hence of good reliability, in practice several uncertainties about the way in which the data are acquired and treated limit its applicability at the scale of individual buildings or specific typology of buildings.

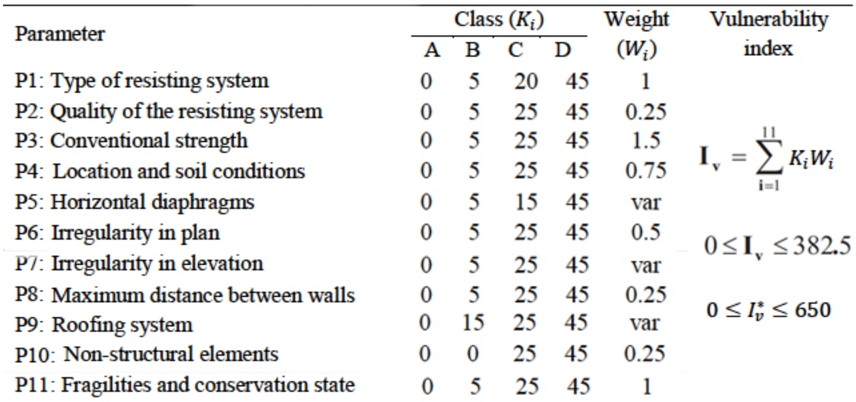
The aim of empirical methods is to derive, from collecting data, a correlation between building typologies and damage level given a seismic intensity and there are two main category of output can be obtained: (i) damage probability matrix (DPM), describes a discrete relationship between the probability of damage occurrence and increasing ground motion severity; (ii) vulnerability function, as a continuous numerical function, expressing the probability of exceeding a given damage state, given a function of the earthquake intensity.

The DPM has been the first vulnerability assessment proposed by Whitman et al. (1973) as a probabilistic approach to predict the damage state, based on observed damage data after san Fernando earthquake 1971, express the probability of obtaining a damage level, due to a ground motion of a given macro intensity. Notwithstanding its widely uses, the DPM may not be applicable as assessment method which reflects our vulnerability concept, because, as widely explained in §5, it describes the vulnerability in term of loss and damage estimation.

The second approach is the vulnerability index method (VIM), an “indirect” method because the relationship between the seismic intensity and the building response is establish through the vulnerability index Iv. The vulnerability index is obtained by a summation of weighted parameters, each associated with a constructional or mechanical characteristic of the building typology, which affects the seismic behavior of building and its vulnerability. The method requires a large amount of damage data collected from on-site survey form which collect information of structural characteristics then used for defining the parameters that influence the vulnerability (e.g. plan and elevation configuration, type of foundation, state of conservation, etc) This method overcome the limitations of DMP approach, in fact, the definition of vulnerability relies only on the buildings feature, while observed damage data are used to calibrate the vulnerability functions for buildings of the same typology, and thus it may be applied in regions having experienced the same level of seismic intercity or PGA, with similar buildings typology.

The first application was developed by Benedetti and Petrini (1984),and then revised by the GNDT (1993) (Gruppo Nazionale per la Difesa dai Terremoti) for the “Second Level Assessment Form” in order to detect constructional features that define the vulnerability at large scale.

The $I_v$ is evaluated using the following equation and relies on 11 parameters (Figure 7) which are combined with a qualification coefficients $K_i$, according with the quality condition from A (optimal) to D (unfavorable) assigned by expert opinions. The vulnerability index ranges from 0 to 382.5, but is generally normalized from 0 to 100, where 0 represents the least vulnerable buildings and 100 the most vulnerable.



| Parameter | Class ($K_i$) | | | | Weight ($W_i$) | Vulnerability index |
|---|---|---|---|---|---|---|
| | A | B | C | D | | |
| P1: Type of resisting system | 0 | 5 | 20 | 45 | 1 | |
| P2: Quality of the resisting system | 0 | 5 | 25 | 45 | 0.25 | |
| P3: Conventional strength | 0 | 5 | 25 | 45 | 1.5 | $\mathbf{I}_v = \sum_{i=1}^{11} K_i W_i$ |
| P4: Location and soil conditions | 0 | 5 | 25 | 45 | 0.75 | |
| P5: Horizontal diaphragms | 0 | 5 | 15 | 45 | var | |
| P6: Irregularity in plan | 0 | 5 | 25 | 45 | 0.5 | |
| P7: Irregularity in elevation | 0 | 5 | 25 | 45 | var | $0 \le \mathbf{I}_v \le 382.5$ |
| P8: Maximum distance between walls | 0 | 5 | 25 | 45 | 0.25 | |
| P9: Roofing system | 0 | 15 | 25 | 45 | var | $0 \le I_v^* \le 650$ |
| P10: Non-structural elements | 0 | 0 | 25 | 45 | 0.25 | |
| P11: Fragilities and conservation state | 0 | 5 | 25 | 45 | 1 | |

*Figure 7: Parameter qualification values for* Benedetti and Petrini (1984)

The most substantial difference between DPM and VIM is that the first one uses discrete vulnerability classes expressed in term of expected damage, the second, provides a continuous vulnerability function where the vulnerability level are readily quantifiable and allows the comparison between different seismic zones.

Further improvements of the VIM method have been developed by various authors for application at different level of details and scale, with the aim of providing correlation between the vulnerability index and the damage ratio to the seismic demand (macroseismic intensity, PGA, spectral demand). Some of them scientific contributions are discussed in the §5.2. The VIM has been further replicated within the RISK-UE Project as one of the vulnerability assessment procedures for the seven European cities chosen as case studies (Barcelona, Bitola, Bucharest, Catania, Nice, Sofia, and Thessaloniki).

One obstacle to the derivation of continuous vulnerability functions is that the macroseismic intensity is not a continuous variable, as vulnerability and damage. This problem was overcome by Spence et al. (1992) by introducing the Parameterless Scale of Intensity (PSI) to derive fragility curves for different building typologies based on the observed damage using the MSK damage scale. Thus, the damage scale and fragility curves are independent of macro seismic intensity scale, because for each type of building it possible to define the level of the scale corresponding to the median of the fragility curve for level of damage D3 (structural damage).

The most common output obtained by empirical methods are damage probability matrices, vulnerability index methods, continuous vulnerability curves or screening methods; each of them has to be calibrated by extensive post-seismic data collection and it may lead to uncertainty of the results. Further development of empirical vulnerability functions evolution has certainly been facilitated by the increases in computational powers, in fact it is proposed alternative normal or lognormal distributions using spectral acceleration or spectral displacement of the elastic period of vibration, rather than macroseismic intensity or PGA to characterize the ground motion. Recent applications based on this approach have been developed by (Sabetta et al. 1998; Rota et al. 2006).

### b. Analytical methods

The analytical methods represent an attempt to overcome the uncertainties associated with empirical approach aiming at obtaining more reliable vulnerability models by combining statistical and mechanical procedure. Indeed, they approach seismic vulnerability issue in structural engineering terms proving a direct relationship among constructional features and mechanical behavior to seismic action.

The improvement of the characterization of seismic hazard in term of spectral ordinates (spectral acceleration, spectral displacement) has not only enabled the development of aforementioned improvement of empirical methods, but also of analytical ones, by representing a single structural units or a given typology of building as a structural model. Therefore, these methods are more appropriate for evaluating cases where construction details are recorded and well understood, and their results may be reliable only for classes of structures which are reasonably well defined in structural terms. The aim of these methods is computing the behavior of such model and damage scenario to expected shaking intensities in essentially two ways: (i) by capacity curve describing building response in terms of performance point which are derived by the intersection of the ground motion demand (spectral acceleration) and the capacity (spectral displacement); (ii) by fragility curves which describe the level of structural damage as damage index or damage thresholds expressed in terms of displacement or drift. This approach could be particularly suitable for assessing vulnerability of a single building or a few buildings of similar typologies. It is also useful to produce scenarios for future event and for evaluating the improved performance due to strengthening interventions and retrofit. The reliability of the results is affected by the availability of specific data about construction details that fully characterize the computed model and thus the structural behavior of buildings.

In the past decade, a significant number of procedure [from HAZUS-MH (FEMA 1999), to SELENA (Molina et al. 2010), (Erberik 2008)] have been proposed and although their output can be expressed by the same fragility/capacity curves, they differ in modeling, numerical complexity of input data and in ground motion measures chosen. Therefore, the curves cannot be easily compared to different areas with diverse construction characteristics. However, analytical vulnerability curves have frequently been used to support the empirical DPMs and vulnerability curves based on the observational damage data, leading to hybrid methods, as discussed in more detail in the next paragraph.

Among analytical methods, further proposals use collapse multipliers calculated from mechanical assumptions which identify the occurrence of different possible failure mechanisms for the given typology and structural characteristics. They are known as **collapse-mechanism methods** and have been particularly applied to masonry buildings. Bernardini et al. (1990) was the first who proposed this approach through VULNUS method for the vulnerability assessment of unreinforced masonry buildings (URM) using the fuzzy-set theory and the definition of collapse multipliers for in-plane and out-of-plane behaviour. Another procedure developed by D'Ayala et al. (1997) is the FaMIVE method (Failure Mechanism Identification and Vulnerability Evaluation) based on a suite of 12 possible failure mechanism validated with in situ observation and laboratory experimental validation. The collapse multipliers are calculated through an equivalent static procedure in order to find the most probable collapse mechanism for both in-plane and out-of-plane failures for each façade wall of the building under consideration.

According to Maio et al. (2018) these mathematical models developed by analytical approach tend to be useless by non-academic audiences due to their complexity, the number of variables involved, their degrees of uncertainty and the ways in which they are combined.

### c. Other classifications

As proposed by Vicente et al. (2014) in addition of the common classification previously described, a brief review of other significant vulnerability approaches is presented below. The main methodologies discussed are then summarized in Appendix 10.6.

The **hybrid methods** try to overcome the main limitations of the previously described methods, making use of different sources of information combined together: vulnerability curves are usually derived from the combinations of observed damage statistics with either expert opinion and/or analytically derived curves from experimental test and structural models. For instance, the Macroseismic methods are based on empirical data and expert judgment or combine empirical data and analytical results; in fact, they derive the vulnerability and damage correlation by combining the typological classes defined by the macroseismic scale EMS-98 and the vulnerability index from empirical method.

The **heuristic approach** relies on expert judgment and on the possibility that a given number of experts will express similar judgment when asked about the performance of a given building typology subjected to a given shaking scenario. This relies on personal observation and experience and it is very useful when no other form of assessment can be carried out, however, the reliability of the outcome can be very low.

The **macroseismic approach** is widely adopted at international level (Ferreira et al. 2014; Chieffo et al. 2019) for largescale seismic assessment of historical centers buildings. It allows to determine the expected damage of constructions, in according to the EMS-98 scale (Grünthal 1998), starting from their vulnerability index.

The **mechanical methods** predict the seismic response of the building by using an appropriate mechanical model of the whole building or of an individual structural element. A method belonging to this group is the limit state method, such as the so called “kinematic” approach that identify by the lowest value of the multiplier load the weakest mechanism and, consequently, the most probable to occur. This method was firstly proposed by Giuffrè (1993), then developed by Bernardini et al. (1990), and D’Ayala and Speranza (2003) and adopted by the Italian seismic code (N.T.C. 2008; O.P.C.M. 3274/2003, O.P.C.M. 3431/2005).

The **conventional techniques** are essentially heuristic methods, they use a vulnerability index to correlate with the level of damage obtaining the capacity of the structure, spectral displacement and inter-story drift limit. They differ to qualify the physical features of structures empirically or by seismic design standards. ATC-13 and the HAZUS methods belong to this class.

## 5.2 Assessing vulnerability of historic masonry buildings and building aggregates

Masonry buildings represent the highest proportion of the building stock worldwide and in regions affected by severe seismicity and they represent the largest proportion of casualties in earthquakes and the huge cost of the post disaster recovery programs. They are widespread in Mediterranean and European historical city centres, and notwithstanding several studies developed on masonry buildings, is still difficult to estimate their performance under earthquake, in absence of reference to seismic standards and code.

The European Union has supported numerous research programs in this particular field, as the ONSITEFORMASONRY (2006), PROHITECH (2009), NIKER (2010), or the PERPETUATE (2014), aimed at developing a methodology for the assessment of seismic risk of cultural heritage assets with the final goal of developing European Guidelines. One of them, the NIKER project (New integrated knowledge based approaches to the protection of cultural heritage from earthquake-induced risk) coordinated by the

University of Padova (Italy), gives an exhaustive understanding of the historic masonry structures that it will properly refer in the current part. Also the EMS-98 scale, within the definition of the buildings typology, clarifies what is the relevant construction factors that must be considered for defining the correct seismic response which affect the overall vulnerability of a structure. These factors, which are generally applicable to all types of structures, both engineered and non-engineered, are: the quality and workmanship ("rule of art" - *regola d'arte*), the state of preservation, the regularity, the ductility, the position, strengthening interventions, the earthquake resistant design (ERD), the building importance. Some of these are already discussed in the previous paragraphs.

Extensive damage surveys, carried out on the centres affected by recent earthquakes, have demonstrated that still remain a lack of knowledge about the real structural behavior of historic masonry buildings, and is well known the requirement of a deep understanding of the construction. This learning process encompass the "diagnosis" of the all of construction features in order to understand the role of all features and details, the characteristics of the materials and its eventual evolution in time, by using both experimental investigation on-site and in the laboratory and structural analysis based on appropriate mathematical models (Binda et al. 2007).

The process usually starts with the reconstruction of the historic evolution of a building or of an aggregate by a historical documentary research and collection (texts which describe the architecture of the building, old graphic documents, old photographs, drawings, old aerial photographs of the area in which the building could appear…). Although the time of construction may not be accurately determined, temporal and spatial information of the growth of the urban centre can provide a first overview about typologies of building and local construction features by the comparison between past and present cadastral maps (Vicente et al. 2014). The building in its current layout is the result of a continual transformations and the identification and the analysis of its evolution along the time is a very important step in order to check the vulnerable elements that can cause structural faults and influence its seismic performance. This research is also essential to find the resisting original structural system and vulnerabilities such as lack of connection between portions of the building or of the adjacent SU within an aggregate building, in order to identify possible discontinuities in the walls, floors and roofs. In fact, the occurrence of a peculiar out of plane mechanism depends on the level and type of connection of the façade to the side walls, floor and roof.

In fact, the absence of effective connections between intersecting walls and between walls and horizontal structures may cause kinematic mechanisms related to the loss of equilibrium of structural portions rather than to states of stress exceeding the materials ultimate capacity (Giuffrè and Carocci 1999).

Based on the observation of real seismic failure modes of historical and traditional buildings in Italy, Giuffrè (1990), proposed an approach for the study of the seismic vulnerability of masonry buildings based on their decomposition into rigid blocks with the aim of define two collapse mechanisms (first damage mode and second damage mode) that are analyzed by applying kinematic limit analysis. According to Giuffrè (1993) definition the "First Damage Mode" is always ruinous because cause the overturning of the whole wall panel or of a significant portion of it, while the "Second Mode of Damage" (in-plane) can be checked only when the "first mode" doesn't occur thanks to metallic connections. This approach is particularly interesting as a tool for seismic analysis of buildings which do not conform to box behavior due to the lack of connection between façade and party wall and between floors.

Moreover, the construction type, quality and state of preservation of masonry play a fundamental role in determining the capacity of a construction to sustain seismic actions. This problem has to be studied until others mechanical issue because a masonry which can resist and transfer the vertical and seismic forces without breaking up should have geometric and physical characteristics that permit a monolithic behaviour (Borri and De Maria 2009). However, double-leaf or multi-leaf masonry, which is widely used in historic structures, could demonstrate the non-monolithic behaviour, and in this case, masonry becomes a governing parameter for the behaviour of historic buildings. Masonry with disconnected leaves is extremely vulnerable, especially against horizontal seismic actions that induce out-of-plane mechanism. Giuffrè (1990) carried out the first experimental and analytical studies about the mechanical behaviour of the stonework masonry typologies based on the recognising of “rule of art” (*regola d’arte*) characteristics after visual inspection, survey and typological classification that was reported in abacus for all the case studies analyzed. He identified some characteristic, like the connection elements called headers, that can influence the loadbearing wall mechanical behaviour.

Of course, others important information to be collected are: the typology and morphology of the load-bearing masonry walls to verify the regularity of the distribution of windows and doors, and the eventual presence of a-seismic device and strengthening or repair interventions carried out after previous earthquakes or to repair existing damages, in order to check their effectiveness.

The importance of horizontal elements in terms of strength of the floors and horizontal stiffening, often plays a key role in deciding the vulnerability of a structure. Although it may be difficult or impossible to determine from the outside of a building, it is very important to be able to examine this parameter, in order to assess the vulnerability correctly.

For all the reasons discussed, historic masonry buildings require a distinct care and specific approach in considering the huge presence of architectural peculiarities (Table 3). Moreover, within the purpose of the current research work of assessing the vulnerability of the BE in open space, it is necessary to adopt a reliable methodology according with the main problems of masonry structures in order to achieve a measure of physical damage caused by buildings affecting the surrounding space. The latter aim will widely discuss in the following D1.2.2.

| STRUCTURAL CHARACTERISTICS OF MASONRY BUILDINGS | | | |
|---|---|---|---|
| | Data | Weakness | Mechanical behaviour |
| **HISTORIC EVOLUTION** | - age<br>- transformation in elevation and in plan | - lack of connections walls, floors, roof<br>- interaction between SU in building aggregates<br>- out of plane mechanism | - box behaviour |
| **MASONRY QUALITY “Rule of art”** | - typological classification (n. of leaf)<br>- material and elements (headers, mortar…)<br>- state of preservation | - masonry collapse | - macro element<br>- monolithic behaviour |
| **LOAD-BEARING WALLS** | - slenderness<br>- distribution of windows and doors | - in plane mechanism | - macro element<br>- monolithic behaviour |

| | | | |
|---|---|---|---|
| **STRENGTHENING INTERVENTIONS** | - anti-seismic device<br>- retrofitting interventions | - out of plane mechanism | - box behaviour |
| **HORIZONTAL STRUCTURES** | - type of floor<br>- strength and stiffening | - out of plane mechanism | - box behaviour |

*Table 3: Summary of main structural characteristics of masonry buildings influencing behaviour under seismic event*

Notwithstanding the classification of the seismic vulnerability presented in §5.1, Maio et al. (2018) proposed a novel complete classification  that highlights three essential aspects (Figure 8):

- detail level of the elements analyzed, and hence the detail of the input data, which depend also on the purpose of the assessment. In fact a large-scale assessments require simple and mainly qualitative data provided by census data or municipalities archives or by on-site inspections; despite mechanical approaches rely on a higher quality of information of the building stock; finally, numerical models depend on complete information of single buildings and their geometrical and material features due to the high computational effort.
- type of output criteria, depends on the number of steps required by the assessment procedure and is distinguished in: direct if use only one-step to estimate damage, such as typological and mechanical approach; indirect techniques require two-step, for instance scoring methods firstly find a vulnerability index and then obtain the damage associated; hybrid technique combine the two one, for example macroseismic method by Lagomarsino and Giovinazzi (2006).
- data and tools quality criterion refer to the quality of the input data and follows the same classification introduced above; in fact, the uncertainty level of the results strongly depends on the reliability of the data input.

Most of the empirical approach gives only qualitative results that have to be interpreted by engineering and compared to the value of the same masonry structures. Indeed, it is also useful to combine different approach for comparing the results and obtaining reliable vulnerability assessment. On the other side, when the complexity of the structure is given by its evolution along the centuries starting from a simple volume to a more and more complex volume, the analytical modelling has to take into account all the vulnerabilities accumulated during the subsequent transformations and should consider significant effect of the construction technique on its structural performance (Binda et al. 2003).

In the following section all of the main procedures are briefly described taking into account their limits and advantages and also the attention of the construction features discussed in this paragraph.

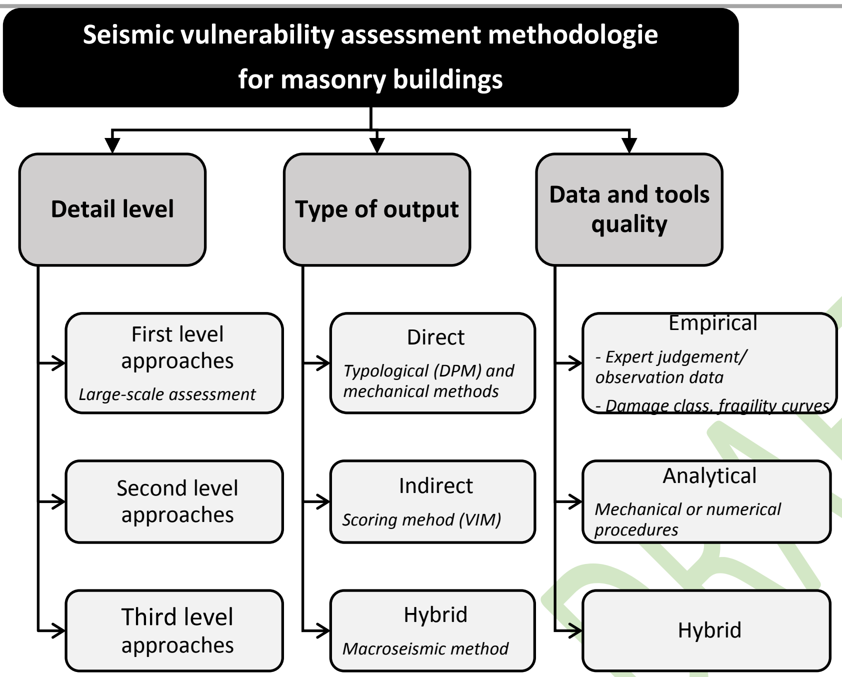


*Figure 8: Flow diagram of criteria for the classification of existing methodologies, revision to (*Maio et al. 2018)

### a. Overview of main methodologies

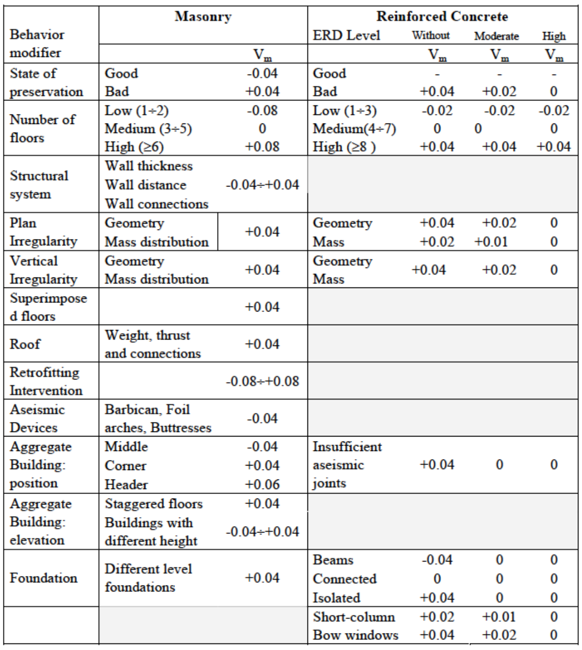
The following paragraph investigate the most significant methods of the seismic vulnerability of historic masonry buildings, with the aim of identifying methodologies' gap and opportunities to enhance the knowledge level on this particular field of the research.

**Giovinazzi and Lagomarsino** (Giovinazzi 2005; Lagomarsino and Giovinazzi 2006) have proposed a correlation between the two empirical approaches and tackled the problems related to the "incompleteness" of the matrix by assuming a definition of damage state and DPM as function of Iv according to the EMS-98 macroseismic scale. The damage probability matrix has been produced for six different classes of decreasing vulnerability (from A to F) and contains a qualitative description of the typology of buildings belonging to each damage grade for different levels of intensity. in this way, they overcome the problem about vulnerability definition by DPM, because they have investigated the vulnerability in terms of construction features. This method can be applied both for the analysis of single building or set of building. In order to complete the vulnerability index $I_v$, which contains only structural information from the typology classification of buildings of EMS-98, three specific indices have been added as suggested by the equation (5):

$$V = V_0 + \Delta V_r + \Delta V_m \tag{5}$$

The $\Delta V_r$ is a regional vulnerability factor, is introduced to take into account the typifying of some building typologies at a regional level: a major or minor vulnerability could be indeed recognized due to some traditional constructive techniques for building classified as belonging to same building typology or vulnerability class in different regions. It is based on the expert judgment or on the available historical data (about observed past damage data).

The behaviour modifier factor $\Delta V_m$ is evaluated as the sum of the scores $V_{m,k}$ of the recognized behaviour modifiers (Figure 9). As observed by EMS-98 macroseismic scale, the seismic behaviour of a building does not only depends on the behaviour of its structural system but it is affected by many other factors such as the quality of the construction:



| Behavior modifier | Masonry | | Reinforced Concrete | | | |
|---|---|---|---|---|---|---|
| | | | ERD Level | Without | Moderate | High |
| | | $V_m$ | | $V_m$ | $V_m$ | $V_m$ |
| State of preservation | Good<br>Bad | -0.04<br>+0.04 | Good<br>Bad | -<br>+0.04 | -<br>+0.02 | -<br>0 |
| Number of floors | Low (1÷2)<br>Medium (3÷5)<br>High (≥6) | -0.08<br>0<br>+0.08 | Low (1÷3)<br>Medium(4÷7)<br>High (≥8 ) | -0.02<br>0<br>+0.04 | -0.02<br>0<br>+0.04 | -0.02<br>0<br>+0.04 |
| Structural system | Wall thickness<br>Wall distance<br>Wall connections | -0.04÷+0.04 | | | | |
| Plan Irregularity | Geometry<br>Mass distribution | +0.04 | Geometry<br>Mass | +0.04<br>+0.02 | +0.02<br>+0.01 | 0<br>0 |
| Vertical Irregularity | Geometry<br>Mass distribution | +0.04 | Geometry<br>Mass | +0.04 | +0.02 | 0 |
| Superimposed floors | | +0.04 | | | | |
| Roof | Weight, thrust and connections | +0.04 | | | | |
| Retrofitting Intervention | | -0.08÷+0.08 | | | | |
| Aseismic Devices | Barbican, Foil arches, Buttresses | -0.04 | | | | |
| Aggregate Building: position | Middle<br>Corner<br>Header | -0.04<br>+0.04<br>+0.06 | Insufficient aseismic joints | +0.04 | 0 | 0 |
| Aggregate Building: elevation | Staggered floors<br>Buildings with different height | +0.04<br>-0.04÷+0.04 | | | | |
| Foundation | Different level foundations | +0.04 | Beams<br>Connected<br>Isolated | -0.04<br>0<br>+0.04 | 0<br>0<br>0 | 0<br>0<br>0 |
| | | | Short-column<br>Bow windows | +0.02<br>+0.04 | +0.01<br>+0.02 | 0<br>0 |

*Figure 9: Parameters of the behaviour modifier factor (Giovinazzi 2005)*

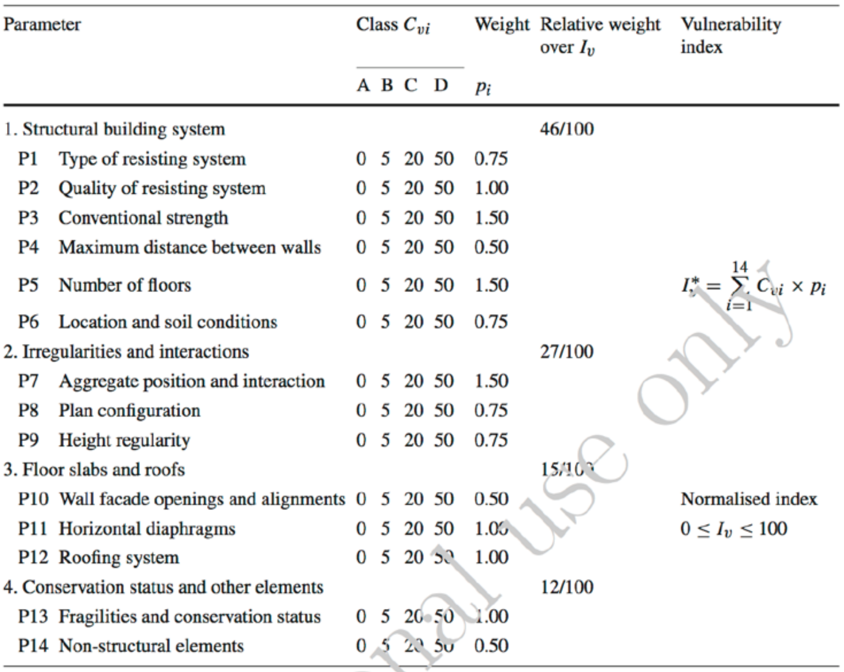
The modifying scores $V_{m,k}$ are attributed on the basis of expert judgment. They have been partially calibrated by the comparison with previous vulnerability evaluation and on the damage observation.

The filter function $\Delta V_f$ is function of the parameter and it is defined depending on the quantity and quality of the available data in order to represent an acceptable approximation of the final vulnerability index value.

Two further behaviour modifier factors have to be computed in the vulnerability index (equation 6) evaluation in order to consider specific features of historical urban context: the historical centre behaviour modifier factor $\Delta V_{hc}$ and the aggregate behavior modifier $\Delta V_a$. The first one, $\Delta V_{hc}$ is closely linked with the local constructive traditions and moreover with the subsequent modifications suffered by the historical center. For instance, are computed (superimposed floor, annexed building, merging) and the positive presence of aseismic devices (counterthrust arches, tie-rods, obstructing elements, counterthrust bows). Because of the absolute originality of each historical centre, the identification and the weight attribution of the parameters $V_{hc,k}$ must be done at the local scale with the collaboration. The second one, $\Delta V_a$ takes into account the interaction between adjacent buildings considering the irregularity in plan and in elevation (different height of adjacent buildings or staggered floors).

$$V = V_0 + \Delta V_r + \Delta V_m + \Delta V_{HC} + \Delta V_A \tag{6}$$

**Vicente** et al. (2014) used the same GNDT Level II approach for the development of a scoring method that calculates the vulnerability index as the weighted sum of 14 parameters (Figure 10). These parameters represent a building feature influencing building response to earthquake and are related to four classes of increasing vulnerability. The improvement to the Benedetti and Petrini (1984) method was the introduction of new parameters that take into account the interaction between buildings as provided by P5, P7 and P10, describing the height of the building, the interaction between contiguous SU and the regularity of the opening which affect the load path. The parameter P2 encompass the type and the quality of masonry and the quality of connections between walls; through the P4 it is evaluated the potential risk of out-of-plane collapse, and also P11 e P12 by taking in account through the connection between horizontal structures; the P13 evaluates the conservation level of the building considering lack of maintenance.

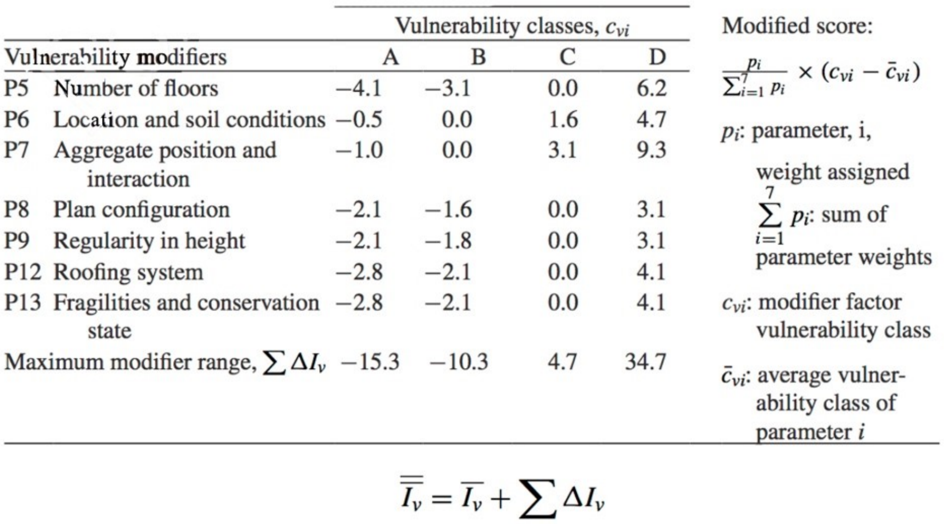


| Parameter | Class $C_{vi}$ | | | | Weight | Relative weight over $I_v$ | Vulnerability index |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | $p_i$ | | |
| 1. Structural building system | | | | | | 46/100 | |
| P1 Type of resisting system | 0 | 5 | 20 | 50 | 0.75 | | |
| P2 Quality of resisting system | 0 | 5 | 20 | 50 | 1.00 | | |
| P3 Conventional strength | 0 | 5 | 20 | 50 | 1.50 | | |
| P4 Maximum distance between walls | 0 | 5 | 20 | 50 | 0.50 | | |
| P5 Number of floors | 0 | 5 | 20 | 50 | 1.50 | | $I_v^* = \sum_{i=1}^{14} C_{vi} \times p_i$ |
| P6 Location and soil conditions | 0 | 5 | 20 | 50 | 0.75 | | |
| 2. Irregularities and interactions | | | | | | 27/100 | |
| P7 Aggregate position and interaction | 0 | 5 | 20 | 50 | 1.50 | | |
| P8 Plan configuration | 0 | 5 | 20 | 50 | 0.75 | | |
| P9 Height regularity | 0 | 5 | 20 | 50 | 0.75 | | |
| 3. Floor slabs and roofs | | | | | | 15/100 | |
| P10 Wall facade openings and alignments | 0 | 5 | 20 | 50 | 0.50 | | Normalised index |
| P11 Horizontal diaphragms | 0 | 5 | 20 | 50 | 1.00 | | $0 \leq I_v \leq 100$ |
| P12 Roofing system | 0 | 5 | 20 | 50 | 1.00 | | |
| 4. Conservation status and other elements | | | | | | 12/100 | |
| P13 Fragilities and conservation status | 0 | 5 | 20 | 50 | 1.00 | | |
| P14 Non-structural elements | 0 | 5 | 20 | 50 | 0.50 | | |

*Figure 10: Parameter qualification of vulnerability index* (Vicente et al. 2014)

The method can be considered robust as it based on expert judgment, it has been validated by inspection and collect accurate geometrical information. The $I_v$ index has upper and lower bounds in order to obtain accurately statistics results and each parameter are associated with a confident level, thus the vulnerability is also coupled to a confidence rating.

The method has also a rapid version in absence of detailed information and it is more suitable to inspecting an urban area because it based on the assumption that masonry building characteristics are homogeneous in the same region. So, the Iv is calculated for those buildings for which detailed information is available, then modifiers factors are calculated for seven parameters, and finally the new Iv index is defined according to the sum of the modifiers parameter scores (Figure 11)



| Vulnerability modifiers | A | B | C | D |
|---|---|---|---|---|
| | Vulnerability classes, $c_{vi}$ | | | |
| P5 Number of floors | −4.1 | −3.1 | 0.0 | 6.2 |
| P6 Location and soil conditions | −0.5 | 0.0 | 1.6 | 4.7 |
| P7 Aggregate position and interaction | −1.0 | 0.0 | 3.1 | 9.3 |
| P8 Plan configuration | −2.1 | −1.6 | 0.0 | 3.1 |
| P9 Regularity in height | −2.1 | −1.8 | 0.0 | 3.1 |
| P12 Roofing system | −2.8 | −2.1 | 0.0 | 4.1 |
| P13 Fragilities and conservation state | −2.8 | −2.1 | 0.0 | 4.1 |
| Maximum modifier range, $\sum \Delta I_v$ | −15.3 | −10.3 | 4.7 | 34.7 |

Modified score:

$$\frac{p_i}{\sum_{i=1}^{7} p_i} \times (c_{vi} - \bar{c}_{vi})$$

$p_i$: parameter, i, weight assigned

$\sum_{i=1}^{7} p_i$: sum of parameter weights

$c_{vi}$: modifier factor vulnerability class

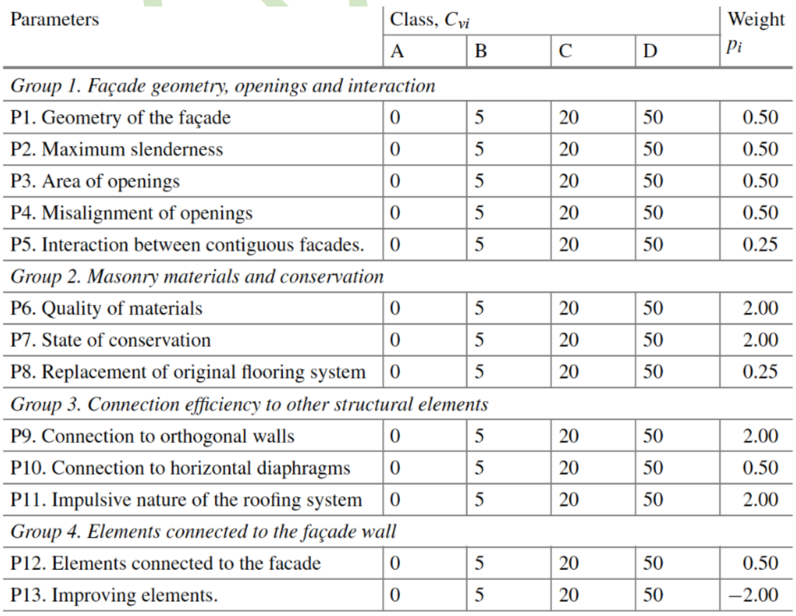
$\bar{c}_{vi}$: average vulnerability class of parameter $i$

$$\overline{\overline{I_v}} = \overline{I_v} + \sum \Delta I_v$$

*Figure 11: Vulnerability modifier factors and score (Vicente, 2014)*

**Ferreira** et al. (2014) proposed a hybrid technique for evaluating the seismic vulnerability of masonry façade walls that is based essentially on VIM methodology. According to this vulnerability formulation, the vulnerability index of the façade wall ($I^*_{vf}$) can be then obtained by the weighted sum of 13 parameters, (Figure 12) related to 4 classes of increasing vulnerability: A, B, C and D.

The vulnerability parameters are arranged into four groups, each of which describe the most important constructive characteristics influencing building seismic response.



| Parameters | Class, $C_{vi}$ | | | | Weight $p_i$ |
|---|---|---|---|---|---|
| | A | B | C | D | |
| *Group 1. Façade geometry, openings and interaction* | | | | | |
| P1. Geometry of the façade | 0 | 5 | 20 | 50 | 0.50 |
| P2. Maximum slenderness | 0 | 5 | 20 | 50 | 0.50 |
| P3. Area of openings | 0 | 5 | 20 | 50 | 0.50 |
| P4. Misalignment of openings | 0 | 5 | 20 | 50 | 0.50 |
| P5. Interaction between contiguous facades. | 0 | 5 | 20 | 50 | 0.25 |
| *Group 2. Masonry materials and conservation* | | | | | |
| P6. Quality of materials | 0 | 5 | 20 | 50 | 2.00 |
| P7. State of conservation | 0 | 5 | 20 | 50 | 2.00 |
| P8. Replacement of original flooring system | 0 | 5 | 20 | 50 | 0.25 |
| *Group 3. Connection efficiency to other structural elements* | | | | | |
| P9. Connection to orthogonal walls | 0 | 5 | 20 | 50 | 2.00 |
| P10. Connection to horizontal diaphragms | 0 | 5 | 20 | 50 | 0.50 |
| P11. Impulsive nature of the roofing system | 0 | 5 | 20 | 50 | 2.00 |
| *Group 4. Elements connected to the façade wall* | | | | | |
| P12. Elements connected to the facade | 0 | 5 | 20 | 50 | 0.50 |
| P13. Improving elements. | 0 | 5 | 20 | 50 | −2.00 |

*Figure 12: Parameter qualification of vulnerability index (Ferreira, 2019)*

The parameters of group 1 and 2 are substantially replicated from the previous formulation of the methodology proposed for Portuguese masonry buildings by Vicente (2014). But differently from its, this procedure specifies with the group 3, the relevance of the connection of orthogonal elements (party wall, horizontal diaphragms and roof) in order to avoid out-of-plane failure mechanisms. With the same aim, also group 4 represents the effective connection between horizontal and vertical structural elements in those cases where it is possible to individuate strengthening action by inspection from outside. These features, not always considered in other scoring methods, are extremely important for preventively identify situations in which failure modes can be triggering.

The next step of the procedure is represented by the correlation between damage, hence a mean damage grade ($\mu_D$) has been estimated for different macroseismic intensities based on the vulnerability index. An analytical expression was developed aiming at correlating hazard I, described in terms of macroseismic intensity scale EMS-98, with the mean damage grade ($0 < \mu_D < 5$) of the damage distribution in terms of vulnerability V and Q, ductility factor that describes the ductility of a certain constructive typology, as shown in the equations (7) and (8) :

$$\mu_D = 2.51 + 2.5 \times \tanh\left(\frac{I+5.25\times V-11.6}{Q}\right) \tag{7}$$

$$V = 0.592 + 0.0057 \times I_{vf} \tag{8}$$

According to other authors, this value leads to the best approximation between mean damage grade values and post seismic damage evaluation for traditional stone masonry buildings. The current methodology was applied to several historical centres (Coimbra, Portugal 2019) with the aim of estimating damage scenarios due to discuss emergency planning strategies.

**Quagliarini** et al. (2019) elaborate a more rapid methodology that permits to obtain a unique vulnerability index for a building aggregate, $VL_{,Agg}$ and $VF_{,Agg}$, coming from the detailed assessment procedure developed by VIM methods of Lagomarsino and Ferreira (mentioned as MVAMs, i.e. Macroseismic Vulnerability AssessmentMethods). The novel equation is developed, as shown in Figure 13, to understand how the vulnerability value of structural units composing the same building aggregate could be influenced by aggregates features (e.g. volumes ratio, differences in building typologies, total number of structural units), including:

- $VL_{,SU}$ or $VF_{,Agg}$ calculated according to (Lagomarsino and Giovinazzi 2006) and (Ferreira et al. 2010)
- the latter vulnerability value is summed and weighted considering the ratio between the volume of each single structural unit ($Vol_{SU}$) and the one of the whole aggregate ($Vol_{Agg}$). Thus, a structural unit with high vulnerability index but with smaller volume in respect to the total aggregate does not influence the overall aggregate vulnerability like a structural unit with the same vulnerability level but with more extended dimensions.
- the parameter *d* considers the more frequent masonry typology within the aggregate and evidences the presence of structural units having different masonry typologies;
- *1/q* represents a corrective factor (> 1), that takes into account the number of structural units within the aggregate due to the impact of the interference effects among them.

$$V_{L,Agg} = \left( \frac{\sum_n \left[ \left( Vol_{SU} / Vol_{Agg} \right) V_{L,SU} \right]}{d} \right) * \frac{1}{q}$$

$$d = \begin{cases} 1 \text{ if structural units have the same masonry typology} \\ 1 - \dfrac{\text{number of different structural units from principal typology}}{\text{total number of structural units composing the aggregate}} \end{cases}$$

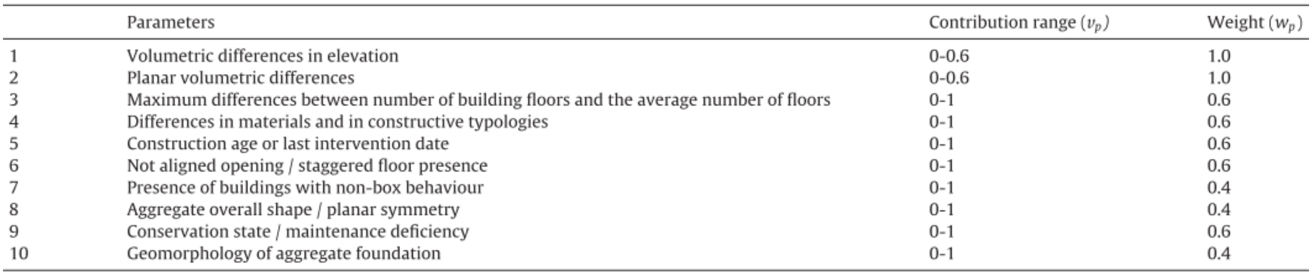
$$\frac{1}{q} = \begin{cases} 1 \text{ if only one structural unit is present} \\ \dfrac{\text{total number of structural units composing the aggregate}}{\text{total number of structural units composing the aggregate} - 1} \end{cases}$$

*Figure 13: novel vulnerability function for building aggregates and corrective factors (Quagliarini et al. 2019)*

Then, the proposed approach has been calibrated by comparing results to existing SISMA method (Mazzotti 2008) used for assessing the aggregate seismic vulnerability at the urban scale of Italian historical centres. This phase could be considered as a first attempt to prove the reliability of the proposed methodology. In fact the vulnerability index has been calculated for each of three methods and results highlight that the (Lagomarsino and Giovinazzi 2006) approach has been considered the most suitable MVAM, so that it was used for carrying out the novel vulnerability index for building aggregates. Therefore, a regression lines related to the vulnerability indexes of the novel proposed approach (using Lagomarsino MVAM vulnerability index) and SISMA have been calculated and a satisfying correlation between them has been proved. Moreover, the strong correlation between these, could suggest using firstly the SISMA method for its typical rapidity in application and then passing to the other proposed approach by using the regression function.

The purpose of this attempts is to simplify the vulnerability assessment through the implementation of expeditious methods, which require simple information easily available by just an external view of buildings, aiming at evaluating the entire urban centre focusing on aggregates, without losing in reliability.

A brief review of the SISMA (System Integrated for Security Management Activities) method is presented below, in order to understand the information required to the specific ten parameters (Figure 14) used to assess the vulnerability of buildings aggregate.



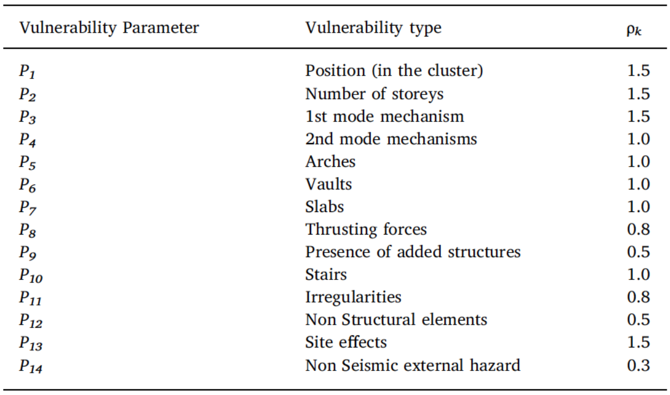
| | Parameters | Contribution range ($v_p$) | Weight ($w_p$) |
|---|---|---|---|
| 1 | Volumetric differences in elevation | 0-0.6 | 1.0 |
| 2 | Planar volumetric differences | 0-0.6 | 1.0 |
| 3 | Maximum differences between number of building floors and the average number of floors | 0-1 | 0.6 |
| 4 | Differences in materials and in constructive typologies | 0-1 | 0.6 |
| 5 | Construction age or last intervention date | 0-1 | 0.6 |
| 6 | Not aligned opening / staggered floor presence | 0-1 | 0.6 |
| 7 | Presence of buildings with non-box behaviour | 0-1 | 0.4 |
| 8 | Aggregate overall shape / planar symmetry | 0-1 | 0.4 |
| 9 | Conservation state / maintenance deficiency | 0-1 | 0.6 |
| 10 | Geomorphology of aggregate foundation | 0-1 | 0.4 |

*Figure 14: Parameters of SISMA method revised by* Quagliarini et al. (2019)

Each parameter is related to the contribution range ($v_p$), which range varies from 0 to 1, and the weight wp. The attribution of the first one is based on the evident differences between the real aggregate and an ideal regular condition, the more these differences are considerable the more each single parameter assumes a higher value. The $w_p$, instead, takes into account the importance of the parameter within the building behaviour.

The main advantage of this methodology is its low requirement in terms of accurate professional skills and data, which are available from on site survey and external investigation. However, some parameters require detailed knowledge of historic transformation and evolution of the aggregate in order to find the best value to the contribution range ($v_p$). For instance, the P5 require chronological information of any retrofitting interventions, which only available from historic data of building report. Moreover, parameter P7 aimed at distinguishing box behaviour of structural units composing the aggregate, needs engineering investigations to detect the presence of ring beams, concrete slabs, metal ties and anchors, stiff horizontal structure, lack of connection between façade and party walls.

Another development of the vulnerability index method (VIM) has been proposed **Brando** et al. (2017) and **Rapone** et al. (2018) for assessing the seismic vulnerability of Scanno. The method was calibrated on the basis of the observations and engineeristic judgements and it relies on 14 vulnerability parameters (Figure 15) representing the potential fragilities of the buildings. Among the most significative parameters there are: P3 and P4 that take into consideration failure modes. The potential out-of-plane mechanisms is evaluated towards high slenderness, low vertical load, opening on the transverse walls, no horizontal restraining elements, widely spaced transverse walls, lack of element connecting masonry leaves thought the thickness of walls. Instead, the in-plane behaviour is caused by the type of masonry layouts and quality, accounting for the stones pattern, the presence of courses, the mortar quality. The parameter P13 takes into account site effects considering the typology of subsoil (slope profile, rigid subsoil, limestones, the presence of clays) in order to detect soil amplification phenomena.
Each parameter is associated with the $\rho_k$ coefficient that varies between 0 and 1.5 (0 indicates that the vulnerability parameter has no influence on the whole building stability, 1.5 indicates maximum influence).



| Vulnerability Parameter | Vulnerability type | $\rho_k$ |
|---|---|---|
| $P_1$ | Position (in the cluster) | 1.5 |
| $P_2$ | Number of storeys | 1.5 |
| $P_3$ | 1st mode mechanism | 1.5 |
| $P_4$ | 2nd mode mechanisms | 1.0 |
| $P_5$ | Arches | 1.0 |
| $P_6$ | Vaults | 1.0 |
| $P_7$ | Slabs | 1.0 |
| $P_8$ | Thrusting forces | 0.8 |
| $P_9$ | Presence of added structures | 0.5 |
| $P_{10}$ | Stairs | 1.0 |
| $P_{11}$ | Irregularities | 0.8 |
| $P_{12}$ | Non Structural elements | 0.5 |
| $P_{13}$ | Site effects | 1.5 |
| $P_{14}$ | Non Seismic external hazard | 0.3 |

*Figure 15: Vulnerability parameters (Brando et al. 2017)*

Subsequently, damage scenarios are represented by the mean damage, expressed as a function of a vulnerability factor V, and the binomial probability distribution given in Figure 16.

$$p[Dm|I] = \frac{5!}{m!\cdot(5-m)!}\cdot\left(\frac{\mu_D}{5}\right)^{m}\cdot\left(1-\frac{\mu_D}{5}\right)^{5-m}$$

$$\mu_D = 2.5\cdot\left[1+\tanh\left(\frac{I+6.25\cdot V-13.1}{Q}\right)\right]$$

$$V = 4.21\cdot i_v^{*3} - 4.00\cdot i_v^{*2} + 1.16\cdot i_v^{*} + 0.53$$

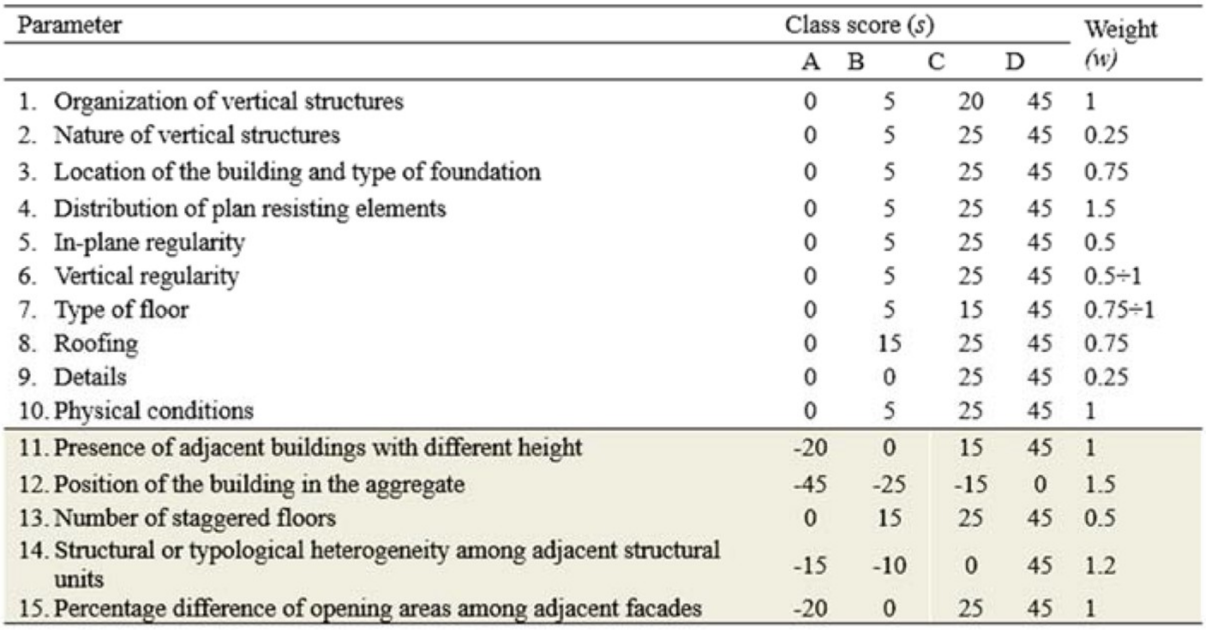
*Figure 16: Binomial probability distribution, mean damage and vulnerability factor*

In detail, V has been expressed as a polynomial function of a mean vulnerability index i*$_v$ (Figure 17), where i$_{v,j}$ is a vulnerability index of the generic building j obtained by the vulnerability assessment, n is the total number of buildings of the historic centre under investigations, and v$_{ki,j}$ and v$_{kp,j}$, are, respectively, scores to be assigned, for each building, to indicators of “fragility” and “protection” corresponding to each seismic parameters ρ$_k$. They vary from 0 to 3, thus the vulnerability index ranges from 0 (no vulnerability) to 1 (maximum vulnerability).

$$i_v^* = \frac{\sum_{j=1}^{n} i_{v,j}}{n} \qquad i_{v,j} = \frac{1}{6} \cdot \frac{\sum_{k=1}^{14} \rho_k \cdot (v_{kf,j} - v_{kp,j})}{\sum_{k=1}^{14} \rho_k} + 0.5 \qquad v_{kf} = w \cdot z \cdot f \qquad v_{kp} = w \cdot z \cdot \eta$$

*Figure 17: Mean vulnerability index, vulnerability index of the generic building j, fagility indicator and protection indicator*

**Formisano** et al. (2016) has developed a new form for assessing the vulnerability of masonry building aggregates based on the Benedetti and Petrini (1984) vulnerability index method by adding five supplementary parameters to the 10 basic parameters of the original form. The introduction of these new parameters takes into account the structural or typological heterogeneity, the interaction effects and the different opening areas among adjacent SUs when they are subjected to seismic actions. Methodologically, the vulnerability index Iv is calculated for each SU of a building aggregates, as the weighted sum of 15 parameters as shown in the previously VIM equations of similar approaches.



| Parameter | Class score (s) | | | | Weight (w) |
|---|---|---|---|---|---|
| | A | B | C | D | |
| 1. Organization of vertical structures | 0 | 5 | 20 | 45 | 1 |
| 2. Nature of vertical structures | 0 | 5 | 25 | 45 | 0.25 |
| 3. Location of the building and type of foundation | 0 | 5 | 25 | 45 | 0.75 |
| 4. Distribution of plan resisting elements | 0 | 5 | 25 | 45 | 1.5 |
| 5. In-plane regularity | 0 | 5 | 25 | 45 | 0.5 |
| 6. Vertical regularity | 0 | 5 | 25 | 45 | 0.5÷1 |
| 7. Type of floor | 0 | 5 | 15 | 45 | 0.75÷1 |
| 8. Roofing | 0 | 15 | 25 | 45 | 0.75 |
| 9. Details | 0 | 0 | 25 | 45 | 0.25 |
| 10. Physical conditions | 0 | 5 | 25 | 45 | 1 |
| 11. Presence of adjacent buildings with different height | -20 | 0 | 15 | 45 | 1 |
| 12. Position of the building in the aggregate | -45 | -25 | -15 | 0 | 1.5 |
| 13. Number of staggered floors | 0 | 15 | 25 | 45 | 0.5 |
| 14. Structural or typological heterogeneity among adjacent structural units | -15 | -10 | 0 | 45 | 1.2 |
| 15. Percentage difference of opening areas among adjacent facades | -20 | 0 | 25 | 45 | 1 |

*Figure 18: The vulnerability form for the assessment of building aggregates* (Chieffo et al. 2019)

The added parameters, shown in Figure 18 and partially derived from previous studies found in literature, detect the construction features and elements that can affect the interaction of adjacent SU in elevation and in plan: (i) presence of adjacent buildings with different height can lead to trigger out-of-plane mechanisms of the highest SU; (ii) position of the building in the aggregate takes into account the in-plane interaction among SU considering four possible positions: isolated, enclosed between buildings, in corner position and in heading position; (iii) number of staggered floors which placed at different heights causing pounding effects to adjacent buildings; (iv) structural or typological heterogeneity among adjacent SU in terms of material and construction technique (e.g. adjacent to a RC structure); (v) percentage difference of opening areas influences negatively the seismic response of the façade in terms of the load path.

In order to obtain a form totally homogeneous with the previous one, the scores and weights assigned were calibrated numerically on the basis of the results of specific numerical parametric non-linear analyses performed by the 3MURI software, which uses the Frame by the Macro-Elements (FME) computational method (Formisano et al. 2015). Then, further development (Chieffo et al. 2019) of the methodology focuses on the comparison between fragility curves and expected damage by using different technique available in literature: the macroseismic (EMS-98) approach, the mechanical method (3MURI software) the kinematic analysis (VULNUS method). The results show that the Vulnus fragility curves are placed in a middle range between the upper limit curves (mechanical method) and the lower limit ones (macroseismic approach) of the fragility domain. This means that the two methods have the same reliability level in predicting the building compound seismic vulnerability.

**D'Ayala** et al. (2003) developed an analytical mechanical approach for the seismic vulnerability assessment of unreinforced masonry (URM) or adobe historic building, the Failure Mechanism Identification and Vulnerability Evaluation (FaMIVE). The FaMIVE method, following an approach first proposed by Giuffrè (1990), models the masonry fabric as an ideal opus quadratum, even though it is may be clearly an abstraction from reality, especially in cases in which the masonry units are only roughly squared and of variable size. The mechanical model uses a nonlinear pseudo-static structural analysis basing on a suite of 12 possible failure mechanism (out-of-plane, in-plane and combined failure modes) which correspond to different constraints condition between the façade and the rest of the structure that are detected after a survey campaign by compiling an electronic form. Using this pre-established set of decisional criteria, collapse mechanisms can be univocally defined and their associated collapse-load multipliers are computed for each façade of a building and the lowest value of them is the lower bound of the level of shaking which will trigger the onset of a specific failure mechanism. Thus, it produces a prediction of most probable damage state and levels of vulnerability for individual or groups of buildings, in relation to expected levels of shaking at a site.

In the second step, the FaMIVE algorithm produces vulnerability functions in terms of ultimate lateral capacity (ESC) for different building typologies, through the evidence collected from extensive in situ damage observation and laboratory experimental validation. The latest version of methodology also yields as output capacity curves, performance points and fragility curves for different seismic scenario in terms of spectral displacement of ultimate acceleration.

The methodology can be applied with a sufficiently detailed analysis of the geometric, typological and structural parameters, which can directly influence the seismic performance of masonry buildings, through the on-site inspection concentrates on those parameters and can be satisfactorily surveyed from the street. In order to minimize the surveying time and the need for pre-existing plans, the operator conducts a preliminary survey of the urban centre under study while collects typological layouts, masonry fabrics, quality of materials and workmanship, which are set of data directly relates to the local construction techniques. Each of the identified typologies are further analysed by a detailed survey only for a limited number of architectural, structural and material typologies present in a given urban centre. Once these are classified, the following step of the survey from the street consists in recognising the pertinence to a given class for the specific features that are recorded in the form. So that it overcomes the lack of available data that can be replaced with these comparative studies about building typologies or typical structural features of local constructions.

Leaving aside the computing procedure and its outcomes, it is worth look at the form used either in a post-seismic scenario, to map the distribution of occurred damage, or as a preventive tool to define strengthening strategies. In particular, the FaMIVE survey form (Appendix 10.7), includes five sections about characterization of geometric and constructive features and one section for detecting damage scenario and failure modes. For each information it is required the quality and the reliability of the input data.

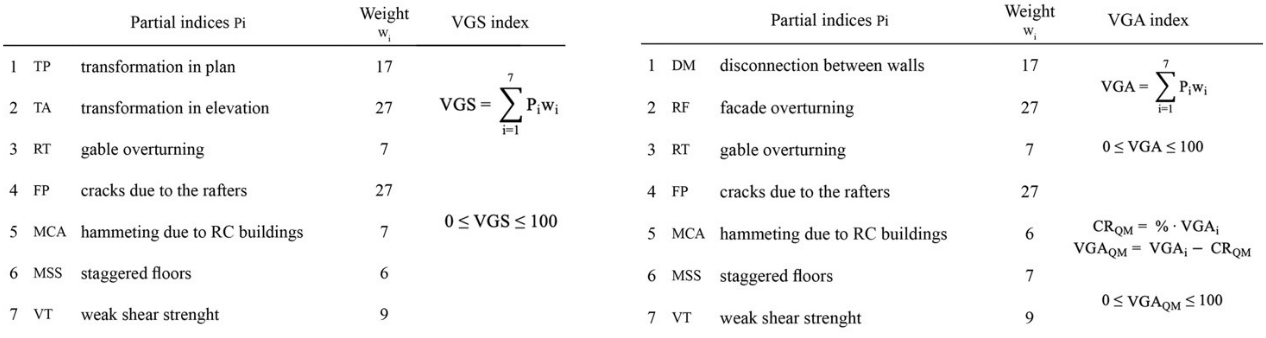
- Section 1 focuses on urban data, such as the position of building within a block or an aggregate and connection to adjacent buildings. The SU position within the building aggregate allows to restrict the possible failure mechanism, for instance, corner failure may not be triggered for interclosed cells.
- Section 2 collect the geometric characteristics of the façade (orientation, dimensions, number of storeys, presence of gable).
- Section 3 records the geometric characteristics of openings, such as the lay-out, the height of the upper horizontal spandrel, the percentage of void between load-bearing walls.
- Section 4 describes the geometry in plan (walls perpendicular to the façade).
- Section 5 focuses on the structural characteristics about the type of horizontal structures, the presence and lay-out of reinforcement, type and quality of masonry (mortar type, size of the elements, headers), presence of further element of vulnerability.
- Further additional elements affecting the vulnerability, such as nonstructural elements (additions, balconies, vaults) are considered in section 6.
- Section 7 is reserved to the level of damage, which is discussed in the D.1.2.2.

**Mochi and Predari** (2016) have carried out a vulnerability assessment method for building aggregates in historical centre based on the determination of synthetic indicators providing a prior prevision of collapse mechanisms (I mode in-plane and II mode out-of-plane) under earthquake by identifying the fragilities of masonry buildings. In fact, the method's assumption is that the seismic damage of the historical building derives from the loss of stability of individual components as rigid blocks, then, from the insufficient shear strength of the walls. It is essentially a scoring method that combine the empirical approach, due to the validation of the parameters by observation damage data and expert judgment, and mechanical/kinematic approach as developed by the studies of Giuffrè. In fact, the starting point of this methodology was represented by the identification of the historical transformation process that leads building aggregate to the current layout through the comprehension of the modification, such as annexed or merged SU, super-elevations, demolitions and reconstructions. This initial phase can only be hypothesized when there is no specific, historical or archaeological documentation, although some indirect sources may constitute an interesting reference base (Mochi 2009).

The synthetic vulnerability indicators require an exhaustive knowledge phase to be acquired, including a preliminary bibliographical research and an on-site survey in order to outline the evolutionary processes suffered by each aggregate in its planimetric and elevation development and to detect all the construction factors (based on techniques and design concepts used in the local area) which directly influence the seismic behaviour of the masonry buildings. On the other hand, the elements that positively influence the seismic response (such as the presence of anti-seismic devices and the good quality of the construction technique) are considered. However, with the aim of accelerating and simplifying the survey phase in case of lack of information, two different procedure have proposed to assess the vulnerability: the expeditious method applied on the façade of the building aggregates and the analytical method calculated on the SUs composing the building aggregate. The first method, since is a quick assessment procedure, requires only a planimetric map and elevation plan to identify the vulnerability indicators of the façade. This application is useful for entire and extensive historical fabrics before carrying out a detailed quantitative analysis. The second procedure is more detailed and requires the ground floor plan and an in-depth investigation. For the planimetric reconstruction of the buildings, are usually used the most recent plants belonging to the cadastral archives, while the quickest and precise choice for the survey of the facades consists in the use of photomodelling tools (Predari et al. 2019).

The global vulnerability index is calculated as a sum of weighted partial indices (Figure 19), on a scale of values from 0 to 100: VGS index (global expeditious vulnerability) for the first methodology, and the VGA index (global analytical vulnerability) for the second one. These partial indicators are obtained from a critical evaluation of buildings technological solutions that can be identified the propensity to damage due to the construction lacks. They are based on the assumption that the out of plane mechanism is triggered from the loss of stability of individual components, which are seen as rigid blocks moving due to the ground acceleration. They summarize the following collapse mechanism:

- RF index: out-of-plane collapse of the façades;
- RT index: out-of-plane collapse of the gable;
- FP index: cracks due to the rafters;
- DM index (disconnection of wall): it derives essentially from the historic transformation processes of buildings and allows to define the portions of façades that can be subjected to out-of-plane collapse, and the width of the fronts to be considered effective for the shear mechanism;
- MSS / MCA index: hammering due to constructive irregularities (as the presence of buildings having a reinforced concrete structure inside the aggregate);
- VT index (weak shear strength): due to insufficient width of the masonry walls.

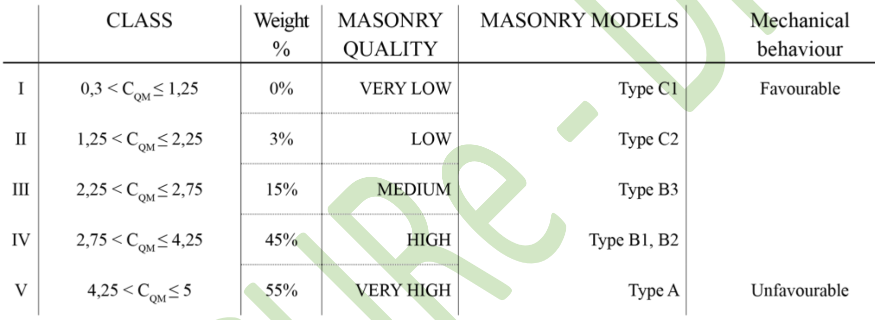


| Partial indices Pi | | | Weight $w_i$ | VGS index |
|---|---|---|---|---|
| 1 | TP | transformation in plan | 17 | |
| 2 | TA | transformation in elevation | 27 | $VGS = \sum_{i=1}^{7} P_i w_i$ |
| 3 | RT | gable overturning | 7 | |
| 4 | FP | cracks due to the rafters | 27 | |
| 5 | MCA | hammeting due to RC buildings | 7 | $0 \leq VGS \leq 100$ |
| 6 | MSS | staggered floors | 6 | |
| 7 | VT | weak shear strenght | 9 | |

| Partial indices Pi | | | Weight $w_i$ | VGA index |
|---|---|---|---|---|
| 1 | DM | disconnection between walls | 17 | $VGA = \sum_{i=1}^{7} P_i w_i$ |
| 2 | RF | facade overturning | 27 | |
| 3 | RT | gable overturning | 7 | $0 \leq VGA \leq 100$ |
| 4 | FP | cracks due to the rafters | 27 | |
| 5 | MCA | hammeting due to RC buildings | 6 | $CR_{QM} = \% \cdot VGA_i$<br>$VGA_{QM} = VGA_i - CR_{QM}$ |
| 6 | MSS | staggered floors | 7 | |
| 7 | VT | weak shear strenght | 9 | $0 \leq VGA_{QM} \leq 100$ |

*Figure 19: Analytical and Expeditious vulnerability assessment score*

Either procedures lead to acceptable level of reliability, though the analytical method yields more suitable results due to the introduction of the masonry quality parameter (Bernabei 2019). It is worth clarifying that this factor has performed within the vulnerability assessment not beside other parameters but beyond, acting as modifier of the VGA index. The assumption on the basis is that the masonry plays a key role in the mechanical behaviour of the macroelement of a construction to sustain seismic actions. Actually, it may be called “mechanism 0-mode”, because it precludes the monolithic behaviour, thus avoiding failure modes, but it could start to crumble. The parameter masonry quality is represented by the coefficient $C_{QM}$ that is computed as a percentage value of the analytical global vulnerability index which encompasses a series of useful information in order to detect the masonry type corresponding to the masonry of the buildings under study. These features are collected as a summary (Figure 20) of the more relevant research in this field by some authors (Giuffrè and Carocci 1999; Borri and De Maria 2015; Boschi et al. 2017) and the classification also refers to class of masonry of the Italian seismic code (NTC08) and the typical masonry model arranged in abacus by Gurrieri (1999) for Umbria and Marche regions. This reference can be replaced by other abacus available for the analysed area. Moreover, the introduction of this parameter allows to take into account the typical construction features of the local buildings.



| | CLASS | Weight % | MASONRY QUALITY | MASONRY MODELS | Mechanical behaviour |
|---|---|---|---|---|---|
| I | $0,3 < C_{QM} \leq 1,25$ | 0% | VERY LOW | Type C1 | Favourable |
| II | $1,25 < C_{QM} \leq 2,25$ | 3% | LOW | Type C2 | |
| III | $2,25 < C_{QM} \leq 2,75$ | 15% | MEDIUM | Type B3 | |
| IV | $2,75 < C_{QM} \leq 4,25$ | 45% | HIGH | Type B1, B2 | |
| V | $4,25 < C_{QM} \leq 5$ | 55% | VERY HIGH | Type A | Unfavourable |

*Figure 20: Classification of masonry quality*

### 5.3 Critical review

The purpose of the BE S2ECURE research project is the evaluation of the impact of an earthquake and damage scenario in open space in historical urban centres. Actually, a huge relevance has the BE conditions and the interaction of buildings facing public space in order to determine the limit condition for building street interference. The only way to quantify this interaction is by evaluating the physical damage of buildings that could occur in a seismic event through the vulnerability assessment of buildings and by calculating the amount of debris could occlude the public space, road or open space. Achieving the first purpose means adopting a reliable approach for assessing the vulnerability of building, indeed, the current work is a useful aid to detecting the available methodologies that consider, in the most appropriate way, all significant construction and structural parameters affecting the buildings behaviour. On the other hand, obtaining the quantification of debris is possible by identifying a relationship between vulnerability function and damage scenario, which argument will be deeply discussed in the D.1.2.2.

One of the huge limitations of scoring methods is that the evaluation of building vulnerability is given by a synthetic index for describing the global behaviour but does not add information about specific parameter, given that the qualitative judgment on partial vulnerability parameters is previously evaluated by the assessors. That may not help to know which are the possible collapse mechanism that could be trigger under a seismic event and, therefore, the expert judgments may seem aleatory especially in absence of certain information of structural characteristics wherever external survey are not sufficient.

Contrary, the significant advantage of mechanical methodologies is that, on the one side, they help to identify local failure modes through the study of the construction features, which are the cause of out-plane and in-plane mechanisms; on the other side, this approach can lead also to the evaluation of the global building aggregate behaviour. Moreover, the mechanical approaches explain in analytical terms the assumption of the "box" behavior and the elasto-plastic behavior of the masonry structures.

The other point of difference between the two approaches is the purpose of the analysis and the level of detail required, for instance the first approaches allow the vulnerability knowledge in statistically terms, the other ones are mainly focused on the local scale of buildings. Either ways can be used to vulnerability assessment of both local and large scale, but the accuracy of the outcome could differ. With this regard, for the aim of the current research we think that the most suitable approach is the mechanical ones that can better describe the "semeiotic" definition of vulnerability proposed in §5. and then directly recognize collapse mechanisms in order to define a measure of physical damage. Within the latter methodologies, the FaMIVE method and Mochi and Predari (2016) method seem to be much closer to that approach because both provide a quantitative and qualitative vulnerability assessment, the first one results in analytical models and the second in an empirical way.

In order to provide a more exhaustive analysis of the methodologies we propose below a brief discussion (summarized in Appendix 10.8 in terms of checking list) of the relevant issues of the vulnerability parameters.

The relevant of historic evolution of building aggregate is not widely considered: Mochi and Predari method uses it as the starting step of the analysis, Lagomarsino referrers to historic process in terms of the structural heterogeneity of building aggregate. The others consider the lack of connection between walls but not as a direct cause of historic transformation processes.

According to Ferreira, among the most frequently observed damage mechanisms in traditional masonry structures located the urban areas, the response of the facade walls is one of the most prevalent and critical ones, not only due to the direct consequences that may result from the partial or global collapse of these elements, but also due to indirect impacts that can arise from that, such as the obstruction of evacuation routes due to the deposition of debris and ruins. For this reason, evaluating the out-of-plane mechanisms by vulnerability assessment method could be very important and plays a key rule especially for achieving the goals of the current work.

Among the methodologies previously discussed, Ferreira e Formisano refer to the failure mode through parameters that identify the connection between the facade and the orthogonal walls, but it is difficult to reveal before for which situations they could be more frequent. While, D'Ayala method permits to univocally defined the probability of a mechanism occurring through the critical value of the collapse load multiplier associated. Mochi and Predari detect out-of-plane mechanism through partial indicators RT, RF and FP, which describe the building facade, gable or corner overturning, that compute the façade's surface prone to collapse.

Shear capacity and in-plane mechanisms are widely computed by all the methodologies by considering the interaction in plane and in elevation of adjacent US in building aggregates, the irregular distribution of windows and doors affected the load-bearing masonry walls.

The state of conservation and the masonry quality are important parameters that are considered by all of methods, but only Mochi and Predari method give a different value to the influence of the masonry quality, using it as external parameter to the vulnerability assessing procedure. The presence of a-seismic devices and eventual retrofitting interventions are also included in all of methods, as parameters that improve the seismic response of façade and avoid out-of-plane mechanisms.

In conclusion, it is worth clarifying that all the methodologies require a huge amount of structural, geometrical and construction information. On the one hand, this guarantees the reliability of the output data, on the other hand, the survey phase requires a lot of time to collect all the information necessary to the assessment. To overcomes the lack of available data, Vicente, D'Ayala, Mochi and Predari use comparative studies about building typologies or typical structures previously in deep studied. Instead, Lagomarsino relies on the expert judgments of the local engineering. Moreover, it is important to highlight that to reach higher levels of details of the analyzed data the use of data inventory, such as GIS, is certainly useful, since available public database is still missing.

## 6. Risk management (RM) and risk matrix

General definitions define risk as "effect of uncertainty in achieving objectives" (ISO 73:2009), hence it is considered a deviation, positive or negative, from what is expected. So that the risk concept is normally correlated to the definition of probability of a particular event occurring and its potential impacts, but it also strictly dependent to the uncertainty which is the state of knowledge or the state of information deficiency necessary for the understanding of a given event, its consequence or probability.

Move from these assumptions, all organizations are subject to risk and uncertainty, and the need to manage risk in a structured way is increasingly recognized. With this regard, the risk management (RM) consists of "coordinated activities to direct and control an organization with respect to risk" (ISO 31000:2009), therefore its process involves several steps such as the identification, analysis, assessment, treatment and monitoring of risk. Moreover, some authors (Kaplan and Garrick 1981) correlate the quantification and the analysis of risk to needs of decision-making context. Moreover, they state that "we are not able to avoid risk but only to choose between risks", so that they emphasize the key role of risk management in providing alternative solutions for reducing the probability and impacts of risks.

International trends in risk awareness places increasing emphasis on providing adequate methodological management practices for organisations and public governance aimed at improving effective strategies to reduce the probability and the impact of particular risk.

Different methods and techniques are used to conduct the process of the risk assessment, that can be classified in qualitative, semi-quantitative and quantitative methodologies (Tixier et al. 2002).The degree of detail required depends on the availability of reliable data, and of the decision-making needs of the organization. The qualitative assessment defines the consequence, probability and level of risk according to linguistic scale criteria. Semi-quantitative methods use numerical scales for consequence and probability and combine them to produce a level of risk using an equation. The quantitative analysis estimates practical values for consequences and their probabilities producing values of the level of risk in specific units according to the context.

## 6.1 ISO 31000: international standard for RM

Among these methodologies, ISO 31000:2018 is currently the international reference standard for risk management, including environmental risks. It is designed to be used broadly, across any organizations, industries and various sectors to provide the best practice standards and guidance to all operations seeking to use the principles of risk management. While based within business and industries organizations, the approach can be also incorporated into the natural risk evaluation thank to its flexibility. The entire risk management process involves different steps as shown in Figure 21 but the way it is performed can vary between models and techniques used to conduct the process for each phase.

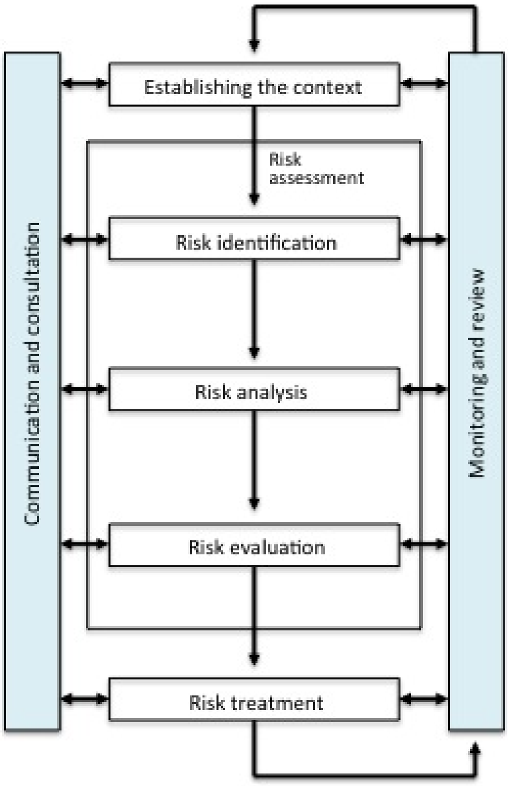


*Figure 21: Risk management process developed by ISO 31000:2009*

In particular, risk matrices are normally adopted supporting risk assessment process due to their ease of use especially in absence of reliable quantitative models for assessing unknown risks, even though that could lead to significant uncertainty. As a management tool the matrix offers a way to provide clarity of risk and to rank alternatives situations under risks, such as different urban scenario and performance under natural disaster, or potential cost due to damage and causalities. The standard template of matrix for risk assessment is that composed in rows and columns defining respectively the categories of likelihood/probability/frequency and impact/consequences/severity of an occurring event.

Identifying the likelihood of most events can be subjective and based upon the knowledge and expertise of those involved in the risk analysis. However, evidence and statistics may be available regarding the recurrence of certain events and can aid to assess the likelihood level. Consequence based on the potential impacts of the risk in hazard prone areas, in fact the assessment is directly linked to the assets analysed. It means that the severity of a natural risk given the same hazard varies between contexts because it strongly depends on the exposed elements.

Risk matrices cannot integrate all that matters using only two variables, thus comes the need to add a third dimension through a scoring mechanism, which explains the relative significance of risks by crossing consequences and likelihood descriptions. Assigning quantitative or qualitative scoring to the cells, such as color-coding and numerical-coding, is an attempt to facilitate rapid communication and understanding of risks by governance in public decision making. It is not necessary to include both qualitative and quantitative descriptor and it depends on the required purpose for the risk assessment. Nevertheless, this type of matrix is really intuitive and the resulting scenarios are easily understood by individuals, it presents some limitations due to its arbitrary construction that can introduce ambiguities and exacerbate errors. For example, the choice of the number of rows and columns, the definition of the categories and the understanding of outcomes. Errors may also be introduced by forcing assigning numerical values (scales) to represent and quantify the categories. Unfortunately, the calculated score is based on subjective judgment and suffers from the same errors in judgment we find in the assessment probability and impact. On the one hand linguistic descriptions of cells given by the combination of row and column categories may be interpreted arbitrary by individuals, on the other hand, converting cells to quantitative values for computing risk scores is arbitrary too. Given that the number scores can either be added together or multiplied, the choice of numerical scale can have a substantial impact on resulting risk score and sometimes explicitly definitions of values are not provided and hence they do not add useful information for risk interpretation. Developing a risk score requires unambiguously specifying the two components in row and column in order to avoid errors introduced by verbal or numerical scaling.

Risk matrices are widely used by organizations of all types and they are serviceable in practical application to a broad variety of risk situations. Within the risk management procedures, the application of matrices is aimed at developing plan for control risk and determine the level of priority required for each risk, and hence its outcomes aid the decision maker for choosing effective actions in reducing potential impact. Recently, risk matrix has been promoted within environmental risk management providing useful tools to governance for improving mitigation and reduction policies to natural disasters.

### a. Risk-based land use planning for natural hazard risk reduction

An innovative risk-based approach (RBA) is presented by Saunders (2012), providing an alternative to the current planning approach that incorporate risk into land use planning decisions for reducing risks from natural hazards. Based on this, the GNS Science in New Zealand proposed a guide and toolbox of risk-based planning approach (RBPA) to land use where consequences of natural hazard events are the focus, in order to assist governance and planners in defining levels of risk and to promote a risk-based land use policy and sustainable plan development in extreme risk areas. This risk-based approach is consistent with international risk management guidelines (ISO 31000:2009), and hence its risk management process relies on five-step, as shown in figure Figure 22.

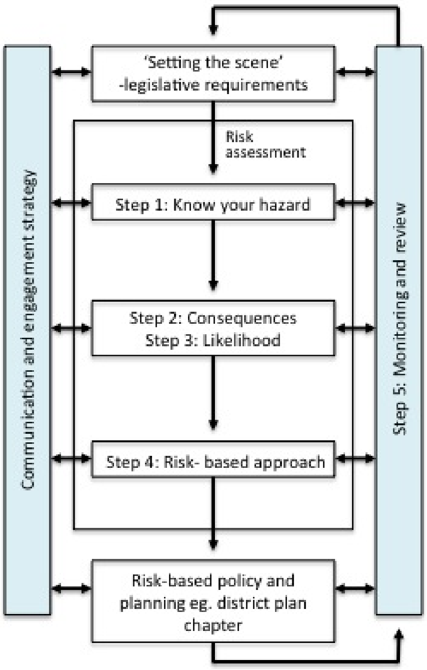
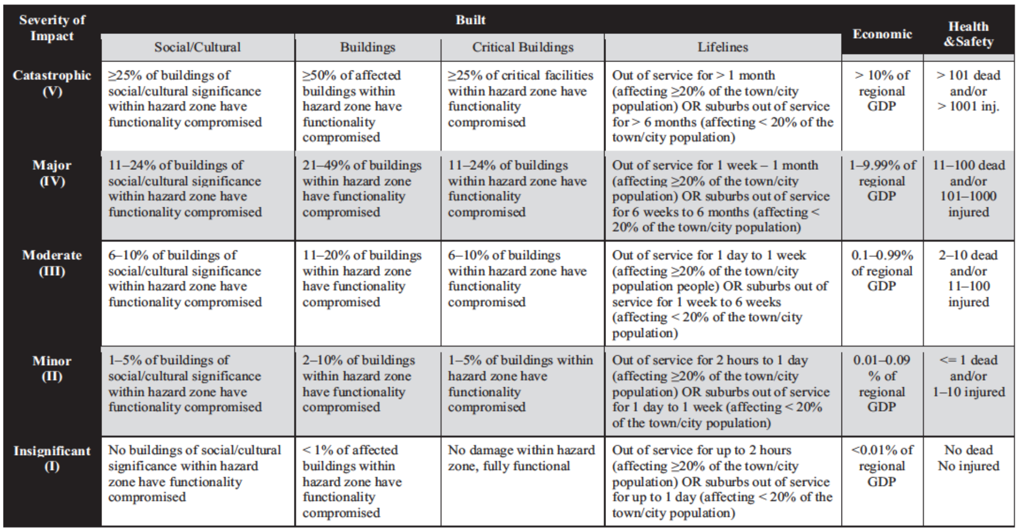


*Figure 22: RBPA process adopted for the management of natural risk in New Zealand* (Saunders and Kilvington 2016)

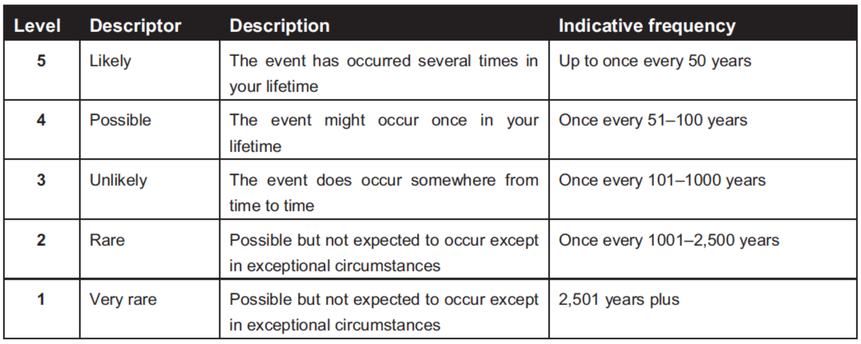
Step 2 is aimed at examining the consequences (Figure 23) of a natural hazard event and involves several aspects that are innovative in current risk-based planning. The purpose of the matrix is to provide decision makers with a robust and transparent framework for assessing and measuring risk, with a focus on consequences. In fact, consequences of a natural hazard event are calculated using a consequence matrix based on the hazard map and land uses within the hazard zones. The impact descriptions of the matrix are based on sources readily available and applicable to local government and measures are based on percentages rather than nominal numbers in order to take into account a scale of the population at risk. In assessing consequences, the final overall level of impact is determined by the consequence category (built, economic, health and safety) with the highest severity.



| Severity of Impact | Built | | | | Economic | Health &Safety |
|---|---|---|---|---|---|---|
| | Social/Cultural | Buildings | Critical Buildings | Lifelines | | |
| Catastrophic (V) | ≥25% of buildings of social/cultural significance within hazard zone have functionality compromised | ≥50% of affected buildings within hazard zone have functionality compromised | ≥25% of critical facilities within hazard zone have functionality compromised | Out of service for > 1 month (affecting ≥20% of the town/city population) OR suburbs out of service for > 6 months (affecting < 20% of the town/city population) | > 10% of regional GDP | > 101 dead and/or > 1001 inj. |
| Major (IV) | 11–24% of buildings of social/cultural significance within hazard zone have functionality compromised | 21–49% of buildings within hazard zone have functionality compromised | 11–24% of buildings within hazard zone have functionality compromised | Out of service for 1 week – 1 month (affecting ≥20% of the town/city population) OR suburbs out of service for 6 weeks to 6 months (affecting < 20% of the town/city population) | 1–9.99% of regional GDP | 11–100 dead and/or 101–1000 injured |
| Moderate (III) | 6–10% of buildings of social/cultural significance within hazard zone have functionality compromised | 11–20% of buildings within hazard zone have functionality compromised | 6–10% of buildings within hazard zone have functionality compromised | Out of service for 1 day to 1 week (affecting ≥20% of the town/city population people) OR suburbs out of service for 1 week to 6 weeks (affecting < 20% of the town/city population) | 0.1–0.99% of regional GDP | 2–10 dead and/or 11–100 injured |
| Minor (II) | 1–5% of buildings of social/cultural significance within hazard zone have functionality compromised | 2–10% of buildings within hazard zone have functionality compromised | 1–5% of buildings within hazard zone have functionality compromised | Out of service for 2 hours to 1 day (affecting ≥20% of the town/city population) OR suburbs out of service for 1 day to 1 week (affecting < 20% of the town/city population) | 0.01–0.09 % of regional GDP | <= 1 dead and/or 1–10 injured |
| Insignificant (I) | No buildings of social/cultural significance within hazard zone have functionality compromised | < 1% of affected buildings within hazard zone have functionality compromised | No damage within hazard zone, fully functional | Out of service for up to 2 hours (affecting ≥20% of the town/city population) OR suburbs out of service for up to 1 day (affecting < 20% of the town/city population) | <0.01% of regional GDP | No dead<br>No injured |

*Figure 23: Consequence matrix* (Saunders and Kilvington 2016)

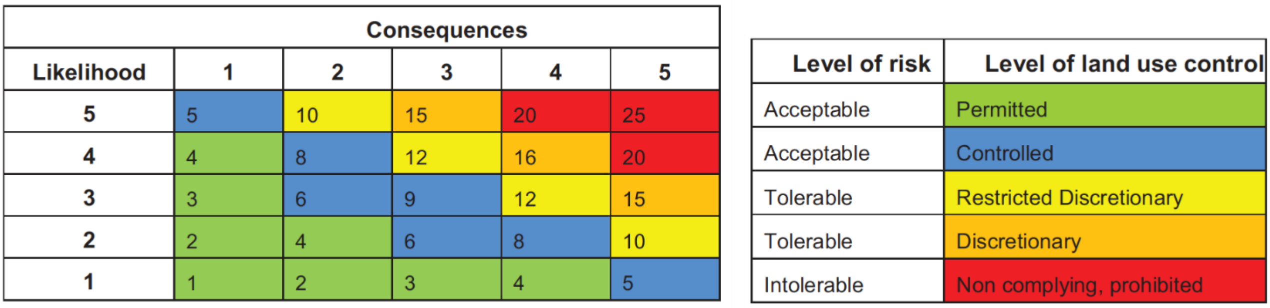
Step 3 is focused on the determination of likelihood (Figure 24) which involves technical input of typical planning timeframes stated by the New Zealand Building Act 2004.



| Level | Descriptor | Description | Indicative frequency |
|---|---|---|---|
| 5 | Likely | The event has occurred several times in your lifetime | Up to once every 50 years |
| 4 | Possible | The event might occur once in your lifetime | Once every 51–100 years |
| 3 | Unlikely | The event does occur somewhere from time to time | Once every 101–1000 years |
| 2 | Rare | Possible but not expected to occur except in exceptional circumstances | Once every 1001–2,500 years |
| 1 | Very rare | Possible but not expected to occur except in exceptional circumstances | 2,501 years plus |

*Figure 24: Likelihood scale of RBPA* (Saunders and Kilvington 2016)

Even though the RBPA recommends carrying out consequence analysis prior to likelihood analysis, the assessing may be interchangeable and can even occur simultaneously. Once the two dimensions are determined, the step 4 is the focus point of the RBPA because leads to establish overall levels of risk, using previous outcomes. Levels of risk are represented by the matrix (Figure 25) further translate into thresholds of acceptable, tolerable or intolerable risk for land use planning linked to public policy. The matrix is populated with quantitative risk level, expressed as a function of (consequences) x (likelihood). The numerical value does not relate to any specific quantity but is merely a number to categorize a level of risk (Figure 25). Instead, the colour-coded allows a faster assessment of risk levels and is used as descriptors for different land use controls and activities.



| | Consequences | | | | |
|---|---|---|---|---|---|
| **Likelihood** | **1** | **2** | **3** | **4** | **5** |
| **5** | 🟦 5 | 🟨 10 | 🟧 15 | 🟥 20 | 🟥 25 |
| **4** | 🟩 4 | 🟦 8 | 🟨 12 | 🟧 16 | 🟥 20 |
| **3** | 🟩 3 | 🟦 6 | 🟦 9 | 🟨 12 | 🟧 15 |
| **2** | 🟩 2 | 🟩 4 | 🟦 6 | 🟦 8 | 🟨 10 |
| **1** | 🟩 1 | 🟩 2 | 🟩 3 | 🟩 4 | 🟦 5 |

| Level of risk | Level of land use control |
|---|---|
| Acceptable | 🟩 Permitted |
| Acceptable | 🟦 Controlled |
| Tolerable | 🟨 Restricted Discretionary |
| Tolerable | 🟧 Discretionary |
| Intolerable | 🟥 Non complying, prohibited |

*Figure 25: An example of levels of risk and associated levels of land use control* (Saunders and Kilvington 2016)

### b. Scenarios analysis for environmental risk

Another example of RBA is based on the development of scenario analysis that is usually adopted to business domain, however, recently became common for assessing environmental risk, e.g. climate change related risks and their potential implications, also by non-financial companies. There is not available a systemic literature of guideline for developing scenario process, nevertheless some authors (Kosow and Gaßner 2008) a good insight of this domain by identifying characteristics and typologies among the multiplicity processes of scenarios.

Some risks are known to exist, but are difficult to articulate, in terms of their likelihood, magnitude, and their severity of impacts, and particularly difficult to understand due to limited historical precedents to learn from. Fundamentally, scenarios are used to better understand the various dimensions of a risk and explore the range of potential resulting consequences; are not intended to represent a full description of the future, but rather to highlight central elements of a possible future and to draw attention to the key factors that will drive future developments. Given the importance of forward-looking assessments of climate-related risk, scenario represents an essential tool to help governments and societies in enhancing critical strategic thinking aimed at mitigating and responding to disaster risks. Its development is crucial at all levels, and involve every branch of society, generating a better sense of risk, preparedness among the population and aid governance to understand the efficacy decisions to DRR.

The Cambridge Centre for Risk Studies has provided a "scenario best practices" for disaster risk reduction domain (Strong et al. 2020). The purpose of the report is provided an accessible guide to scenario analysis, that is a systematic method for exploring how a complex and diverse array of risks may impact a society, by describing stories of plausible futures to be debated. Scenarios is a useful tool for RM to cope with uncertainty, especially in the case of risks that are not well understood or cannot be quantified or even identified. The framework for scenario development proposed follows systematic and recognizable eight core steps (Figure 26).

*Figure 26: Scenario development framework for disaster risk reduction* (Strong et al. 2020)

Although the structure is presented as linear step-by-step, the scenario process might be an iterative one, in which stakeholder engagement provides opportunities for review and revision to ensure it succeeds.

## 7. Proposal for seismic risk assessment on OS

The previous brief literature yields a good overview of the risk management domain and appropriate scenario processes recently adopted for environmental risks, in order to identify techniques more suitable for our intent. In fact, the purpose of this stage is to carry out a seismic risk assessment aiming at understanding of possible consequences of an earthquake in open space. The methodological approach proposed is a combination of scenario process and conventional RBA by adopting matrix techniques to correlate different concepts and visualise outcomes useful to evaluate risk reduction strategies.

The definition of seismic risk encompasses several issues that require a deep knowledge in order to detect the correct inter-relations between variables that ultimately determine the outcome. Previous discussion highlights that managing seismic risk requires specific engineering judgments and modelling. So that, our attempt to assess seismic risk encompasses all the information discussed in the previous paragraphs with the aim of proving a scientific basis of our proposal. In general, assessment of earthquake's consequences is usually developed at global scale, where the impact of the earthquake is controlled by the distribution and severity of shaking, the population exposed to each shaking intensity level, and how vulnerable that population is to building damage at each intensity level. According to this rationale, our attempt is focuses on the assessment of an earthquake impact starting from physical damages of BE that may affect people living or standing in an open space. So that, the probability and the severity of increasing impacts of an earthquake occurring are described by hazard, vulnerability and exposure parameters through two different matrices either related:

- the first matrix (*M1 – Damage matrix*) encompasses hazard (expressed in term of return period) and vulnerability (classes of buildings or buildings aggregates performed by specific methods §5.2) information in order to provide a qualitative assessment of physical damage (debris), which will be quantified by geometric methodologies deeply discussed in §3.2 of D1.2.2;
- the second matrix (*M2 – Consequence matrix*) connects the human exposure, in terms of inhabitants and users of buildings and open areas, as proposed in the §4.3, with the possible damage scenarios resulted from M1, considering how physical damages, produced by buildings facing open space, affect the safety of people and the emergency paths.

The outcomes of the M2 describe possible scenarios outlining social and physical consequences of seismic events; moreover, they may be useful to risk management, on the one side, for evaluating priority strategies of protection of human life and safety in order to plan evacuation paths during emergency, on the other side for identifying necessary retrofitting interventions aimed at avoiding building's failure and damage. The idea behind the "consequence matrix" is placing the focus of attention on certain aspects that may be controlled by handling two key factors: robustness of BE and preparedness of communities, as shown in Figure 27. This procedure allows to generate orientation regarding future DRR strategies and aids to evaluate which decisions are necessary and more adequate to achieve better risk scenarios.

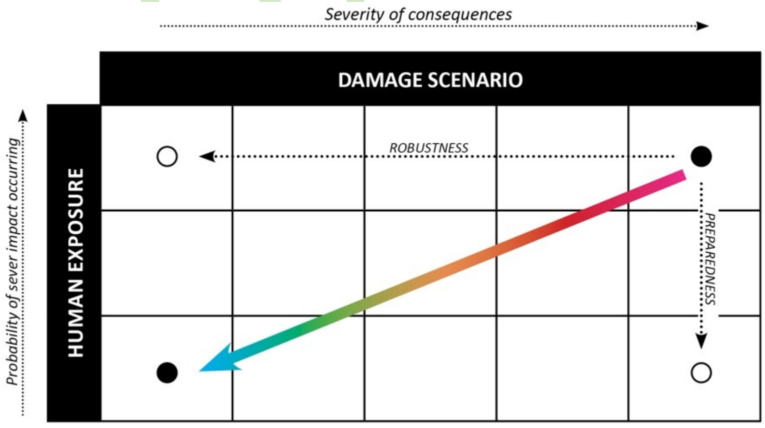


*Figure 27: Application and purposes of Consequence matrix (M2) for DRR strategies*

### 7.1 M1 - Damage matrix

Nowadays, available models that summarize vulnerability, hazard and physical damage are available in term of fragility function, for analytical approach, or DPM (Damage Probability Matrix), for empirical approach. However, these models strictly depend on the accuracy and the completeness of the method adopted for assessing the vulnerability of buildings or building aggregates. So that, also the accuracy of the prediction and quantification of damage (debris) strictly depends on the reliability of the value of the vulnerability index and on other issues discussed in D1.2.2.

Given that complexity, we propose a matrix that describes the correlation between hazard, in terms of Return Period (RP), which can be correlated to the local value of PGA, provided by Italian building code (NTC2018), and vulnerability of building or building aggregates, expressed in term of classes of vulnerability derived from the assessment method used (§5.2), with the aim of providing damage scenarios of BE. Further development will be focused on the quantification of the amount of debris of higher damage state of the matrix through a numerical function suggested in D1.2.2. So that, the Damage matrix provide the probability for buildings belonging to a given class of vulnerability of being subjected to a certain level of damage for increasing probability of certain earthquake occurring. Due to the high amount of damage scenario that can be performed, we undertake two version of M1: the extended form (Figure 28) and the simplified form (Figure 29). They differ only in the range of values of RP adopted; this choice will be detailed explained in the following parts.

- **Column category: Vulnerability**

The columns are referred to the vulnerability index (0 - 100 scale of values) calculated by assessment method, chosen between these previously discussed, and determine the range of the vulnerability into three main classes: low, medium and high. This classification takes into account the possible behavior of building aggregates or buildings under earthquake starting from the objective structural condition, so that the expected damage may be estimated due to the characteristics of construction and its weakness. The "high" class includes index value higher than 50, because we supposed that the vulnerability assessment should consider higher weight to parameters described out of plane mechanisms that lead to the worst severity of damage level. The vulnerability class is selected for each continuous built front (CBF) surrounding the area under study. So that, if an open space has 4 CBF, it will have four different damage scenarios resulted from the matrices.

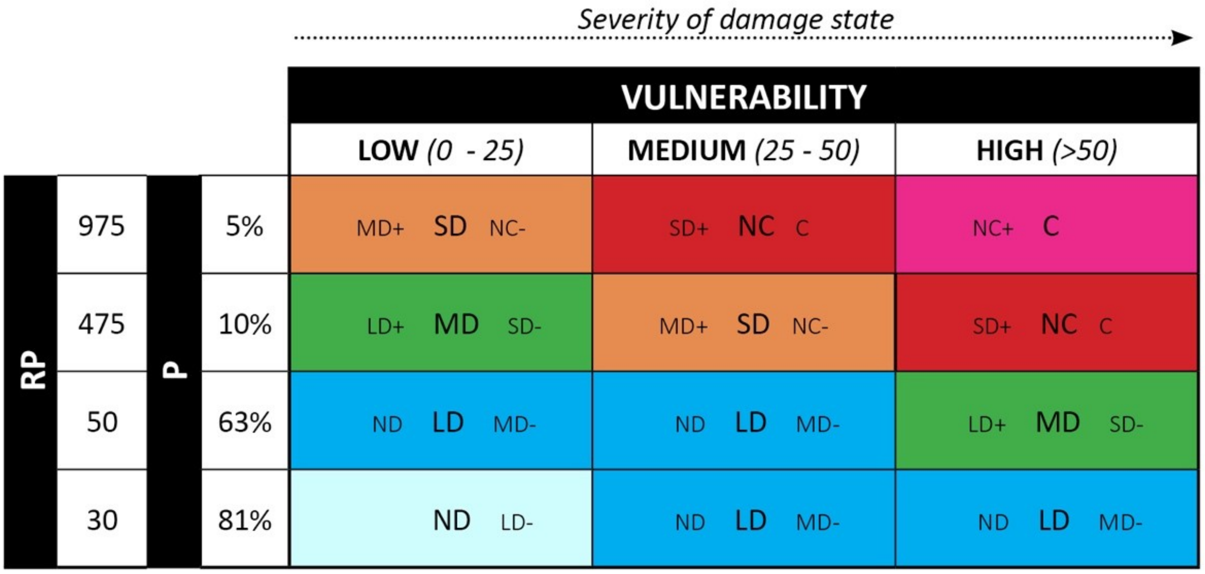
- **Row category: Probability (P) and Return Period (RP)**

The hazard is explained in terms of return period and probability of exceedance in a reference period of 50 years, according to PSHA (probabilistic seismic hazard assessment) model. The return period (RP) is a range of years during which is supposed that earthquake of specific intensity in a specific location may occur and it also expressed as a probability of exceedance. For the current matrix, the RP and P values rely on the hazard maps, developed by Meletti and Montaldo (2007) within the MPS04 project, that demonstrate the distribution and variation of PGA value for nine probability of exceedance in 50 years, each of them corresponding to relative return period. As can be seen by maps (Figure 30), the hazard (PGA value) increases as probability decreases. In general, PGA vary from values less than 0.025g (81% of probability) to 0.7g (2% of probability), but they strictly depend on the site belonging to the specific seismic zones, regulated by the seismic classification (Table 1, Appendix 10.1). So that, given the high variation of PGA values between different geographical areas of the entire Italian territory per P and RP, it is not possible associate the unique PGA value for each rows of the matrix corresponding to the specific P or RP, because different site has different PGA.

| RETURN PERIOD (RP) | PROBABILITY | VULNERABILITY<br>LOW (0 - 25) | VULNERABILITY<br>MEDIUM (25 - 50) | VULNERABILITY<br>HIGH (>50) |
|---|---|---|---|---|
| 2475 | 2% | NC | NC | C |
| 975 | 5% | SD | NC | C |
| 475 | 10% | MD | SD | NC |
| 200 | 22% | MD | SD | NC |
| 140 | 30% | MD | MD | SD |
| 100 | 39% | LD | MD | SD |
| 72 | 50% | LD | LD | MD |
| 50 | 63% | LD | LD | MD |
| 30 | 81% | ND | LD | LD |

*Figure 28: M1 - Damage matrix (extended form)*

Given that the extended version of M1 matrix provides an high amount of possible damage scenario, we preferred to propose the simplified form in order to better explain the development of damage scenario for each cells of the matrix, represented by colour-code. So that, RP = 975, 475, 50, 30 and P = 5%, 10%, 63%, 81% have been adopted as values that are considered by the NTC2018 for ordinary building in the reference period of 50 years for the calculation of the limite state (LS).



| RP | P | VULNERABILITY<br>LOW (0 - 25) | VULNERABILITY<br>MEDIUM (25 - 50) | VULNERABILITY<br>HIGH (>50) |
|---|---|---|---|---|
| 975 | 5% | MD+ SD NC- | SD+ NC C | NC+ C |
| 475 | 10% | LD+ MD SD- | MD+ SD NC- | SD+ NC C |
| 50 | 63% | ND LD MD- | ND LD MD- | LD+ MD SD- |
| 30 | 81% | ND LD- | ND LD MD- | ND LD MD- |

*Figure 29: M1 - Damage matrix for ordinary buildings (simplified form)*

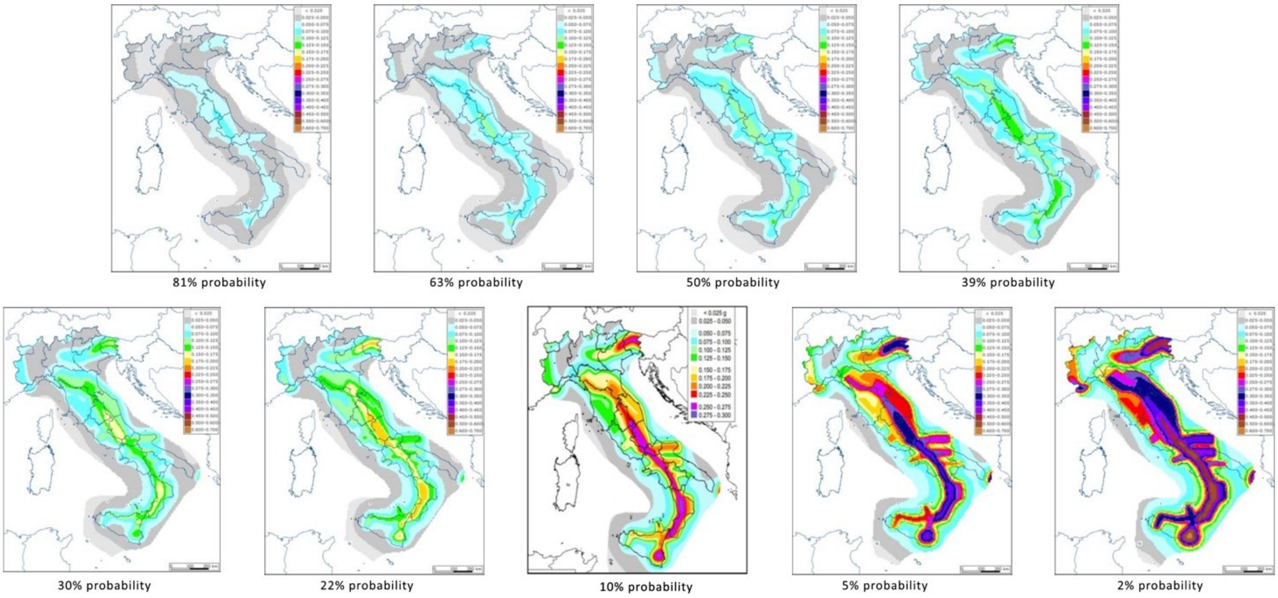


*Figure 30: Hazard maps probability for nine probability of exceedance in 50 years (from 2% to 81%, corresponding to mean return periods from 2475 to 30 years), for type A ground ([http://esse1.mi.ingv.it](http://esse1.mi.ingv.it))* (Meletti and Montaldo 2007)

- **Colour code: scenarios descriptor of damage states**

The colours relate to the cells of the matrix are describing the damage scenarios that explain the possible damage state that building can be reached given its vulnerability for a given exceedance in 50 years. The six damage scenarios proposed are recomputed here retaining similar descriptions using by EMS-98 macroseismic scale (Appendix 10.9) and the damage classification proposed by Novelli (2017) (Appendix 10.10). Contrary to the EMS-98 scale, which provides damage thresholds and not distinct classes, we added the Severe Damage (SD) level (corresponding to the "heavy damage" of the grade 3 of the EMS), explained by Novelli instead. Hence it permits to clearly distinguish also intermediate levels of damage.

In addition, qualitative correlations between damage states and possible damage extent reporting the definition developed by Novelli, in terms of % of macroelement of a building façade, that represents the percentage of mobilised façade and floor structure participating in failure mode (as resulted from FAMIVE analytical method), and Artese et al. (2019) that provide a geometrical relationship, developed from empirical approach, referring to the height of the building façade.

Other authors have discussed how building's debris percentage on the facing street influences the effective emergency path availability, but these will be widely discussed in D122. For the purpose of the current definition of damage scenarios, the relevant assumption is that damage levels less than D4 do not produce road clutter due to the ejected material, so that we indicate damage extent (De) only for Collapse (C) and Near Collapse (NC) damage state.

| ***Level of damage*** | ***Damage state*** | ***Damage scenario description*** | ***Damage extent (De)*** | |
|---|---|---|---|---|
| | | | ***Artese (m)*** | ***Novelli (%)*** |
| **D5** | **COLLAPSE (C)** | Total collapse of entire building or large parts of walls. | 2/3 H<br>(67% height of façade) | 80% $\leq$ De < 100%<br>of macroelement |

| | | | | |
|---|---|---|---|---|
| **D4** | **NEAR COLLAPSE (NC)** | - Serious failure in façade and in gable walls;<br>- Complete detachment between façade and party walls;<br>- Partial structural failure of roof and floors. | | 40% ≤ De < 80%<br>of macroelement |
| **D3** | **SEVERE DAMAGE (SD)** | - Large and extensive cracks in most walls;<br>- Partial detachment between façade and party walls;<br>- Fall of most non-structural elements (chimneys, decorative cornice band…). | 1/3H<br>(33% height of façade) | |
| **D2** | **MODERATE DAMAGE (MD)** | - Moderate cracks in many walls;<br>- Partial collapse of chimneys. | | 0% ≤ De < 40%<br>of macroelement |
| **D1** | **LIGHT DAMAGE (LD)** | - Slight cracks in few walls;<br>- Detachment or fall of large pieces of plaster;<br>- Fall of some parts of non-structural elements. | | |
| **D0** | **NO DAMAGE (ND)** | - Detachment or fall of small pieces of plaster;<br>- Detachment of few tiles or bricks from upper parts of buildings. | | |

*Table 4: Damage scenarios of M1 - Damage matrix*

### a. Discussion and development of chosen damage matrix parameters

It is worth clarifying the choice of some parameters adopted to develop the proposed M1 - Damage matrix, in order to provide an overall insight of the rationale underpinned.

*Return Period (RP)*

The relationship between RP and the probability of exceedance (P) is computed by the equation (9) (Sabetta and Paciello 1995) estimating the trend of the average return period (T) or the frequency of exceedance (1/T). This means that it describes the probability of such a seismic event occurs given a return period *T* in a reference period *t*. Using this relation is possible obtaining statistical analysis of the probability of exceedance (P) choosing for first the reference period *t*.

$$P\ (1, t) = 1 - e^{-t/T} \tag{9}$$

The reference period is established by Italian building code (NTC2018) expressed as $V_R$ by equation (10); it may take a different value because it depends on the choice of $V_N$ and $C_U$, explained in Appendix 10.11. So that the RP established by NTC2018 trough equation (11) that explain the relation between the reference period (VR) and the probability of exceedance (P).

$$V_R = V_N \times C_U \tag{10}$$

$$RP = -\frac{V_R}{\ln(1-P)} \tag{11}$$

Therefore, the Table 5 provides all the possible values of RP performed by the spreadsheet used within the NTC2018, considering four levels of P (81%, 63%, 10% and 5%), in order to choose design strategy and verify buildings seismic performance, in terms of limit states. Moving from these results, four values of RP (30, 50, 475 and 975), corresponding to the reference period $V_R = 50$ for ordinary class of buildings ($C_U = 1$), have been selected for the simplified form of M1 – damage matrix.

| | $V_R$ | 50 | | | 100 | | |
|---|---|---|---|---|---|---|---|
| | $C_U$ | **II 1** | III 1,5 | IV 2 | II 1 | III 1,5 | IV 2 |
| RP | **SLO** | **30** | 45 | 60 | 60 | 90 | 120 |
| | **SLD** | **50** | 75 | 101 | 101 | 151 | 201 |
| | **SLV** | **475** | 712 | 949 | 949 | 1424 | 1898 |
| | **SLC** | **975** | 1462 | 1950 | 1950 | 2475 | 2475 |

*Table 5: Return periods performed by spreadsheet "Spectral responses" (ver. 1.0.3) of Italian NTC2018*

*Limit states (LS)*

The second step for assigning damage scenario to cells of matrix, has been started by considering the description of limit state to the four P and RP class provided by Italian building code (§3.2.1 NTC2018). In fact, as reported by Table 6, these definitions aid to define the damage threshold related to each P and RP aiming at providing damage scenario descriptions. Such damage targets are identified by the following performance levels: Serviceability Limit State (SLO), Damage Limit State (SLD), Life Preservation Limit State (SLV), Collapse Limit State (SLC). Given that limit state (LS) are not as detailed as damage state, for each LS have been associated more than one damage state. In summary, for ordinary buildings ($V_R$ = 50 and $C_{U\ II}$ = 1) NTC2018 assess that for a rare earthquake (475-year return period) the limit state that must not be achieved is the SLV, while damage (SLD) and serviceability (SLO) limit states must not be overcome for a frequent earthquake (50-year return period).

| ***Limit state*** | | ***P*** | | ***Damage state*** |
|---|---|---|---|---|
| **SLO** | Structural and no structural elements are not affected by damage or interruption of serviceability | 81% | ➡ | No Damage (ND)<br>Light Damage (LD) |
| **SLD** | Structural and no structural elements are affected by negligible to slight damages that not affect human safety and building resistance | 63% | ➡ | Light Damage (LD)<br>Medium Damage (MD) |
| **SLV** | - Moderate cracks and partial fall of no structural elements<br>- Substantial damage of structural elements and lack of stiffness to horizontal forces<br>- Good performance to vertical forces<br>- Critic performance near to collapse | 10% | ➡ | Medium Damage (MD)<br>Sever Damage (SD)<br>Near Collapse (NC) |
| **SLC** | - Serious damage of no structural elements<br>- Very heavy damage to structural elements<br>- Total or near total collapse | 5% | ➡ | Near Collapse (NC)<br>Collapse (C) |

*Table 6: Correlation between limit state descriptions (NTC2018) and damage state for each probability (P) values*

This assumption comes also from the fact that each P and RP encompass large range of PGA values differing between seismic zones; so that, in Table 7 upper and lower bounds are considered for each damage state in order to include disparities of expected "damage performance" that may come from belonging to different geographical area in terms of the most possible PGA value occurring.

| *DS* | *Range of damage state* | *Range of PGA* |
|---|---|---|
| **C** | | |
| **NC** | NC+ = C | PGA > 0,25 |
| | | 0,05 < PGA ≤ 0,25 |
| | NC- = SD+ | PGA ≤ 0,05 |
| **SD** | SD+ = NC- | PGA > 0,25 |
| | | 0,05 < PGA ≤ 0,25 |
| | SD- = MD+ | PGA ≤ 0,05 |
| **MD** | MD+ = SD- | PGA > 0,25 |
| | | 0,05 < PGA ≤ 0,25 |
| | MD- = LD+ | PGA ≤ 0,05 |
| **LD** | LD+ =MD- | PGA > 0,25 |
| | | 0,05 < PGA ≤ 0,25 |
| | LD- = ND | PGA ≤ 0,05 |
| **ND** | | |

*Table 7: Upper and lower bounds per Damage States correlated to range of PGA according to seismic classification (§3.1)*

Hence, regarding to this classification, for the matrix damage scenarios we assume that for 50-year return period, the possible damage state is primarily Light Damage (LD), but, depending on vulnerability classes and seismic zone, its upper bound is represented by MD damage state. The choice between them, given the vulnerability class, depending on the expected PGA for the location under investigation. It means that for such seismic event (P = 63%, RP = 50 years) we have to expect low damage levels that do not affect the serviceability of buildings. On the other hand, 475-year return period (P = 10%) includes higher possible damage levels from MD to NC.

### b. Different usage of matrix

Given that damage matrix encompasses many information, it may be used starting from different input depending on the purpose and the available data. Figure 31 shows the HP 1: the first step is selecting the vulnerability class from vulnerability index previously calculated; then, choosing between RP is possible to know all possible damage states are associated to the given vulnerability class with different probability of occurring. For each RP/P row it is possible to know how the range of possible damage states varies between different seismic zone and related PGA values within Italian territory. This way of use is more suitable for general statistical analysis at large scale.

| | | | | **VULNERABILITY** | | |
|---|---|---|---|---|---|---|
| | | | | **LOW** *(0 - 25)* | **MEDIUM** *(25 - 50)* | **HIGH** *(>50)* |
| **RP** | 975 | **P** | 5% | MD+ SD NC- | SD+ NC C | NC+ C |
| | 475 | | 10% | LD+ MD SD- | MD+ SD NC- | SD+ NC C |
| | 50 | | 63% | ND LD MD- | ND LD MD- | LD+ MD SD- |
| | 30 | | 81% | ND LD- | ND LD MD- | ND LD MD- |

**INPUT DATA:**

*STEP 1*: Vulnerability class (Medium)

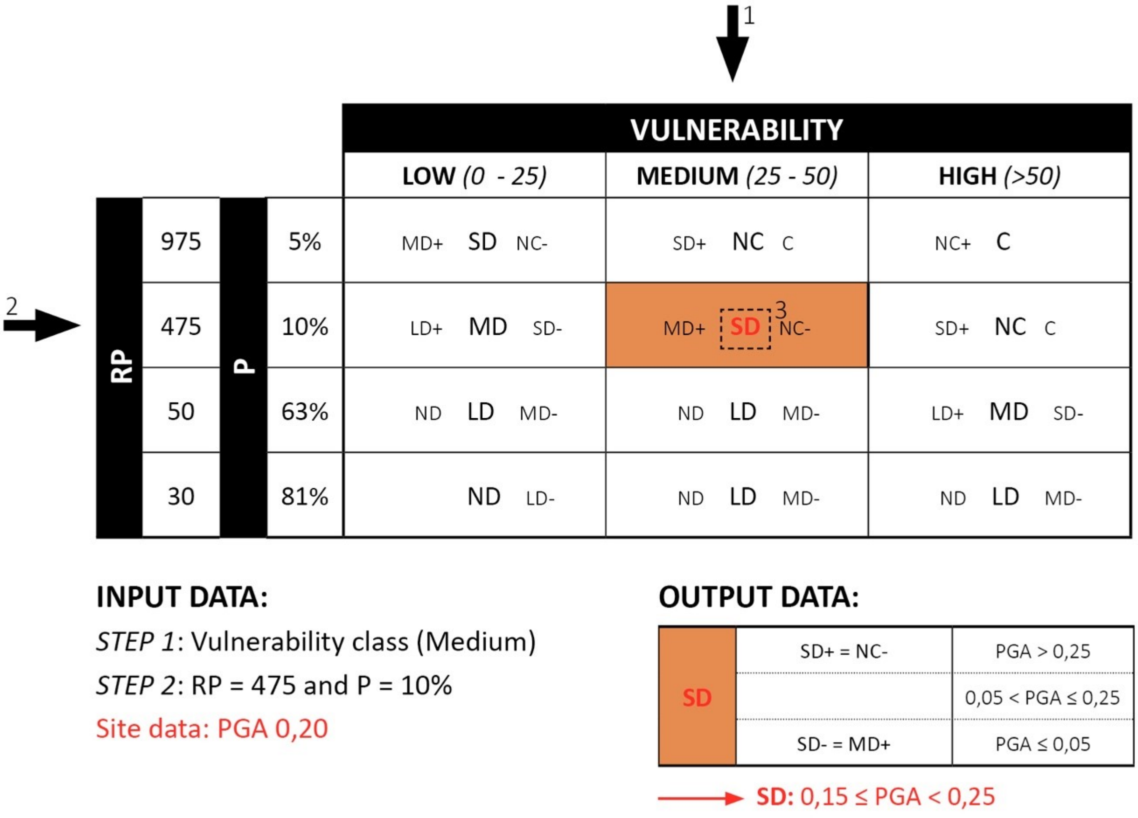
*STEP 2*: RP = 475 and P = 10%

**OUTPUT DATA:**

| | | |
|---|---|---|
| **SD** | SD+ = NC- | PGA > 0,25 |
| | | 0,05 < PGA ≤ 0,25 |
| | SD- = MD+ | PGA ≤ 0,05 |

*Figure 31: HP1 use of Damage matrix*

The second way, HP2, is useful to predict buildings performance under earthquake given a specific geographical location. In fact, we supposed that information about seismic zonation and thus, the corresponding PGA range of values, are available from the spreadsheet "Spectral responses" (NTC2018). Maintaining as first step the selection of vulnerability class, as the RP/P row is chosen, it is possible to determine the unique damage state between the bounds of the resulted cell. Moreover, other detailed information (i.e. spectral response data, medium range of expected Mw) of the site under investigation are available from both microzonation studies (§3.2), seismogenic maps available at online tools, such as DISS (Figure 3). So that, this second way of use matrix is more suitable for the purpose of the current BE SECURE project, because it will be focused on real case studies.



| | | | | VULNERABILITY | | |
|---|---|---|---|---|---|---|
| | | | | **LOW** *(0 - 25)* | **MEDIUM** *(25 - 50)* | **HIGH** *(>50)* |
| **RP** | 975 | **P** | 5% | MD+ SD NC- | SD+ NC C | NC+ C |
| | 475 | | 10% | LD+ MD SD- | MD+ SD NC- | SD+ NC C |
| | 50 | | 63% | ND LD MD- | ND LD MD- | LD+ MD SD- |
| | 30 | | 81% | ND LD- | ND LD MD- | ND LD MD- |

**INPUT DATA:**

*STEP 1*: Vulnerability class (Medium)

*STEP 2*: RP = 475 and P = 10%

Site data: PGA 0,20

**OUTPUT DATA:**

| | | |
|---|---|---|
| SD | SD+ = NC- | PGA > 0,25 |
| | | 0,05 < PGA ≤ 0,25 |
| | SD- = MD+ | PGA ≤ 0,05 |

**SD:** 0,15 ≤ PGA < 0,25

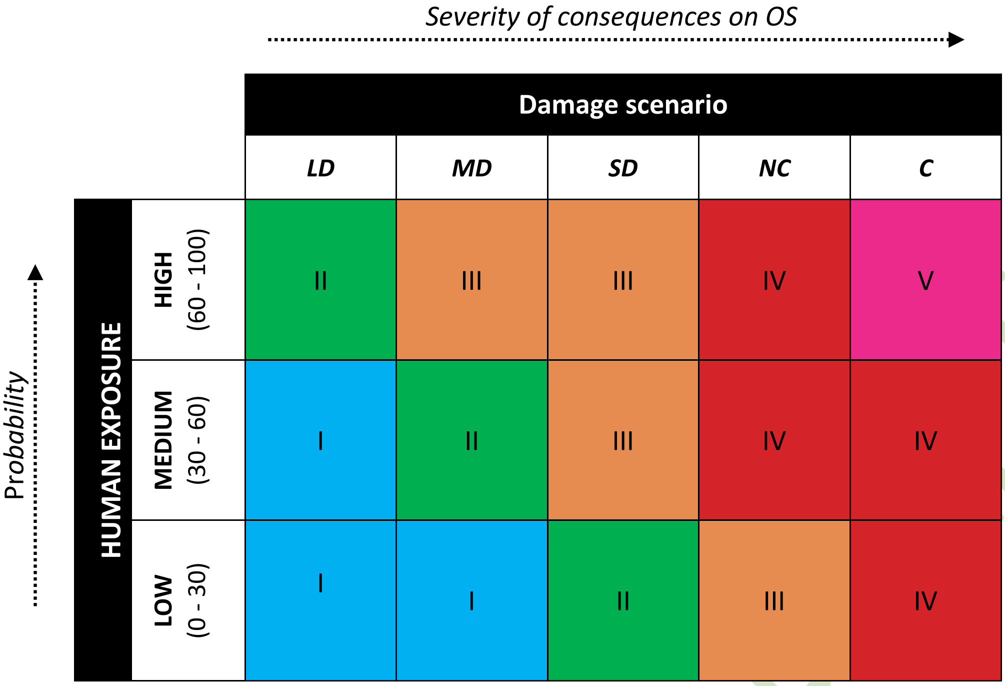
*Figure 32: HP2 use of Damage matrix*

It is worth clarifying that, in recent years, several relationship and equations to correlate Return Period to ground shaking parameters have been developed by authors; nevertheless, given that these parameters differ considerably from geographical location and are strictly dependent on site condition, there is no one correlation that is unambiguously accepted and recognized by entire scientific community.

This fact is one of the reasons that lead us to choose Return Period and Probability of exceedance as parameters of the current Damage Matrix, because they are objective and suitable to be connected to further developments of ground shaking descriptors and models, such as the upcoming hazard maps that will be performed by MPS19 (§3.3).

### 7.2 M2 - Consequences matrix on OS

The consequences scenarios matrix (Figure 33) provides different possible risk conditions of an open space under earthquake by analyzing its exposure and damage scenarios. We should point out that, even though scenarios are described in qualitative terms, they are based on assumptions provided by rigorous scientific analysis. They, hence, supply a hypothetical dimension on the basis of knowledge gained from empirical studies or analytical models, which are deeply discussed in other previous parts of the deliverable. Within the current rationale, the risk is a function of the two dimensions portrayed by the matrix: human exposure and damage state. We assume that rows define category of the probability of impact of event occurring increases as the value of exposure increases, while columns define increasing severity of impacts for increasing damage states of the analysed area.



| | Damage scenario | | | | |
|---|---|---|---|---|---|
| | LD | MD | SD | NC | C |
| HIGH (60 - 100) | II | III | III | IV | V |
| MEDIUM (30 - 60) | I | II | III | IV | IV |
| LOW (0 - 30) | I | I | II | III | IV |

*Figure 33: M2 – Consequences matrix on OS*

- **Columns code: damage scenarios on open space**

The first step relies on the damage scenario resulted from the M1 Damage matrix, varying from left to right, describes the severity of the impact under seismic event. It directly represents how debris falling from surrounding buildings could occlude the urban path and hence influence the usability for emergency evacuation of people and for the access of rescuers. These scenarios also include the information of hazard and buildings vulnerability as input of M1 matrix.

- **Rows code: human exposure**

The exposure, on the left side, describes the probability of occurrence of higher or lower impact which is influenced by higher or lower range of people exposed. The classification encompasses all factors studied by the novel proposal for assessing the exposure considering the human dimension and urban aspects has presented in §4.3.

- **Colour code: scenarios descriptor of consequences**

The consequence table (Table 8) describes the possible scenarios under earthquake based on damage scenario provided by Table 4 and assumption on possible crowding of the open space. These scenarios highlight which situation prohibit people evacuation and life safety.

| ***Level*** | ***Descriptor*** | ***Scenario description*** |
|---|---|---|
| **V** | **CATASTROPHIC** | Negligible safety conditions: debris are such widespread that the 80% to 100% of urban paths are completely compromised. |
| **IV** | **SERIOUS** | Serious safety conditions: until the 80% of emergency path is occupied by debris, and some routes may be entirely blocked. |
| **III** | **MODERATE** | Tolerable safety conditions: the emergency is controlled due to the presence |

| | | |
|---|---|---|
| | | of few debris falling from some buildings or non-structural. But the evacuation is still guaranteed. |
| **II** | **MINOR** | Adequate safety conditions: the emergency is carefully managed because the paths are free and safe. |
| **I** | **NEGLIGIBLE** | Satisfactory safety conditions: the entire urban system is efficient and there is no danger from the surrounding BE. |

*Table 8: Consequence scenario descriptions*

## 8. Conclusion

Finding solution in seismic risk evaluation is one of the greatest challenges faced by engineering nowadays. This deliverable has underlined that the seism risk encompasses different topics from different scientific fields that require an extensive investigation. From the point of view of the hazard, relevant improvements have been made at the nation scale and today the greatest part of the Italian municipalities, in particular those are in seismic prone areas, have zonation plans and detailed investigations from the third level of seismic microzonation. As carefully explained in §4, the exposure may involve different type of element considering at risk due to the purpose of the required analysis. The BE S2ECURE project relies on behavioural models of the people that could be affected by an earthquake, so that, the exposure elements have to be calibrated on human and social factors. With this regard, the proposed state of art highlights that comprehensive studies on human exposure models are still missing in literature, even though further attempts are to improve innovative tools that take into account the temporal dimension of exposure.

The evidence from this work suggests that managing the seismic risk points towards the calibration of reliable procedures for the seismic vulnerability assessment of the urban fabric, with the aim of providing useful tools for reduction and mitigation strategies. Therefore, the detailed and comprehensive literature review of the vulnerability assessment approaches allows us to detect positive aspects and limitations for further applications and improvements. As discussed, the approach adopted strictly depends on the scale of the problem. In particular, empirical methods are more suitable for large scale investigation because guarantee accurate results in statistical terms. Instead, analytical models have important implications for providing detailed analysis of the structural behaviour to be directly correlated to the corresponding damage state. Although these models require a significant computational effort, a wealth of structural data is also necessary for the scoring method. In fact, they substantially differ in calculation procedure, while often the input data may be the same.

Another critical issue regards the particular condition of BE in historical context due to the complexity derived from the evolutionary process in building aggregates and possible transformations, such as retrofitting interventions of SU that may affects the global behaviour of the aggregate. With this regard, all methodologies take into account parameters that encompass these issues, even though the VIM methods in qualitative terms due the fact that they are strongly dependent on judgments from on-site survey that hardly can provide detailed information of historical transformation. To sum up, the critical review has led us to conclude that for the purpose of the current investigation it recommended the choice of two different approaches: one from the VIM methodologies, such as Formisano method that has been comparated and calibrated using also analytical models; the other one, Mochi and Predari method, has an empirical approach but also considers mechanical assumption due to the fact that they are based on historical studies aimed at detecting lack of connection between walls. Using the two methods with different procedure may lead to achieve a greater accuracy of the results, even though they could require further adjustments for finding a reliable correlation with the damage state, that is the focus of the D1.2.2.

Since this detailed overview of the main issue involved with the seismic risk, at the final part of the report an analysis of possible consequences of the earthquake in open space has been proposed by adopting two matrices, as a combination of scenario process and conventional risk-based approach (RBA), in order to determine the correct inter-relations between the three variables (hazard, vulnerability and exposure) and ultimately visualise the outcome useful to evaluate risk reduction strategies.

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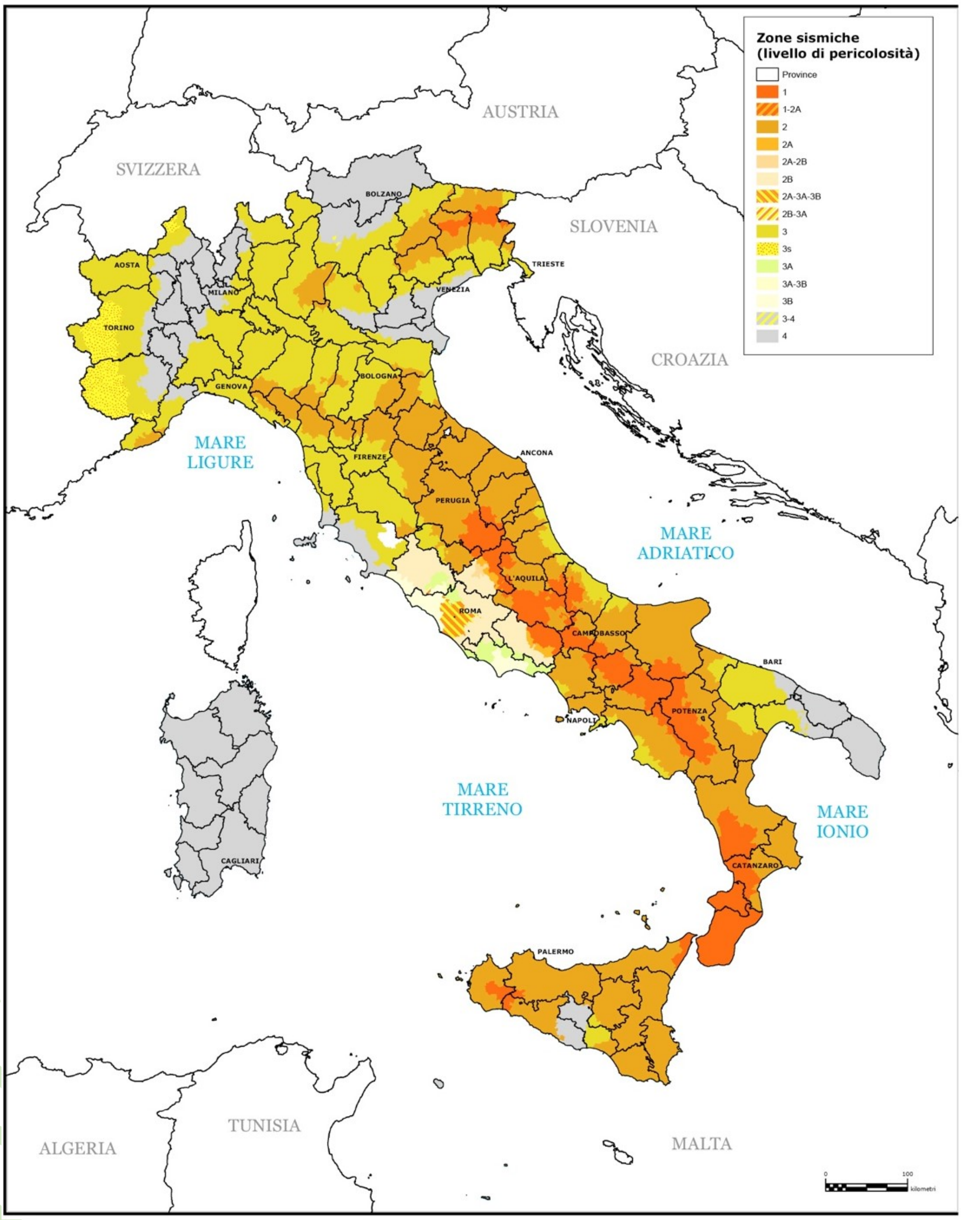
## 10. Appendix

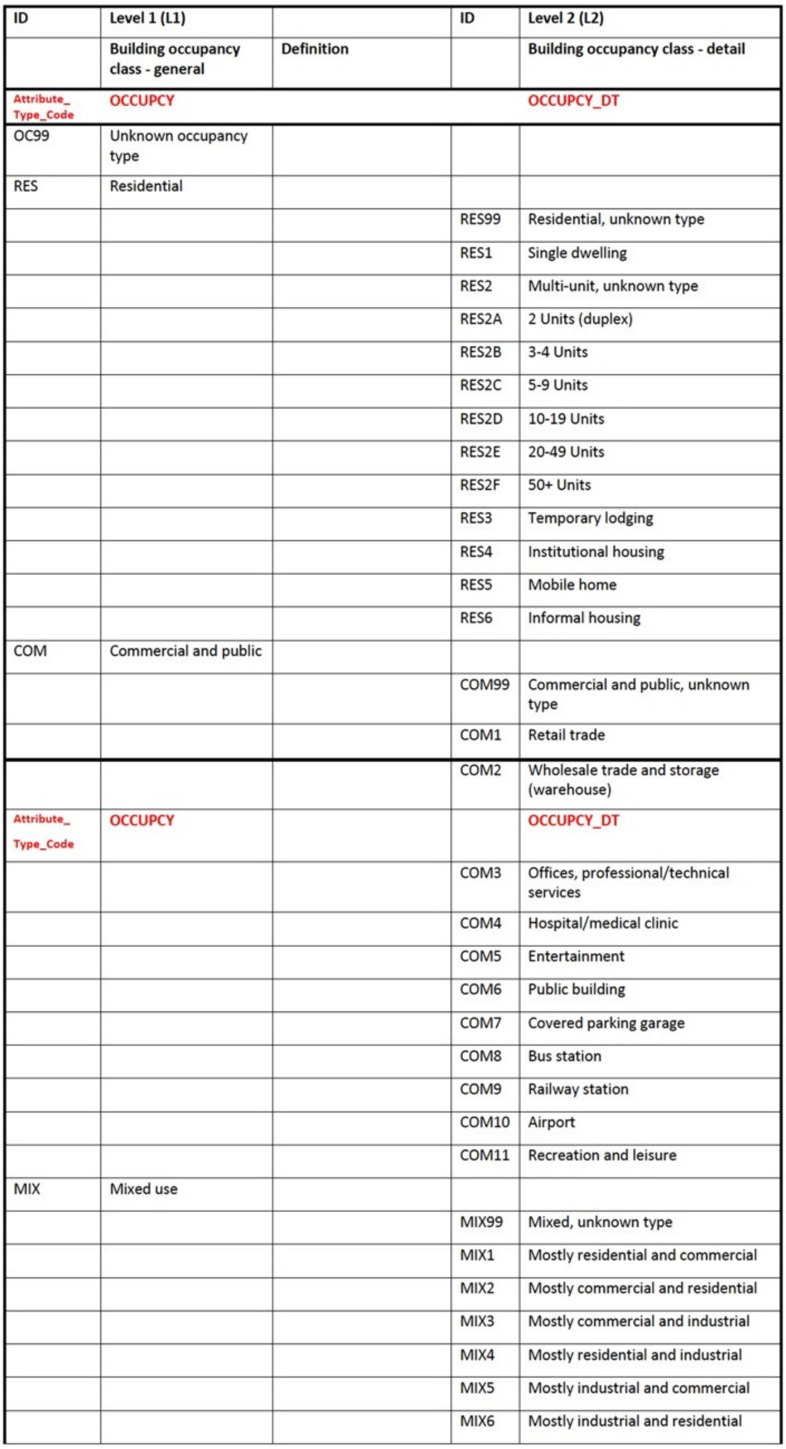
### 10.1 Seismic classification of Italian territory

The current map describes the classification between the four seismic zone of the entire national territory, divided into Provinces, up to 31/01/2020, available online at http://www.protezionecivile.gov.it/attivita-rischi/rischio-sismico/attivita/classificazione-sismica.

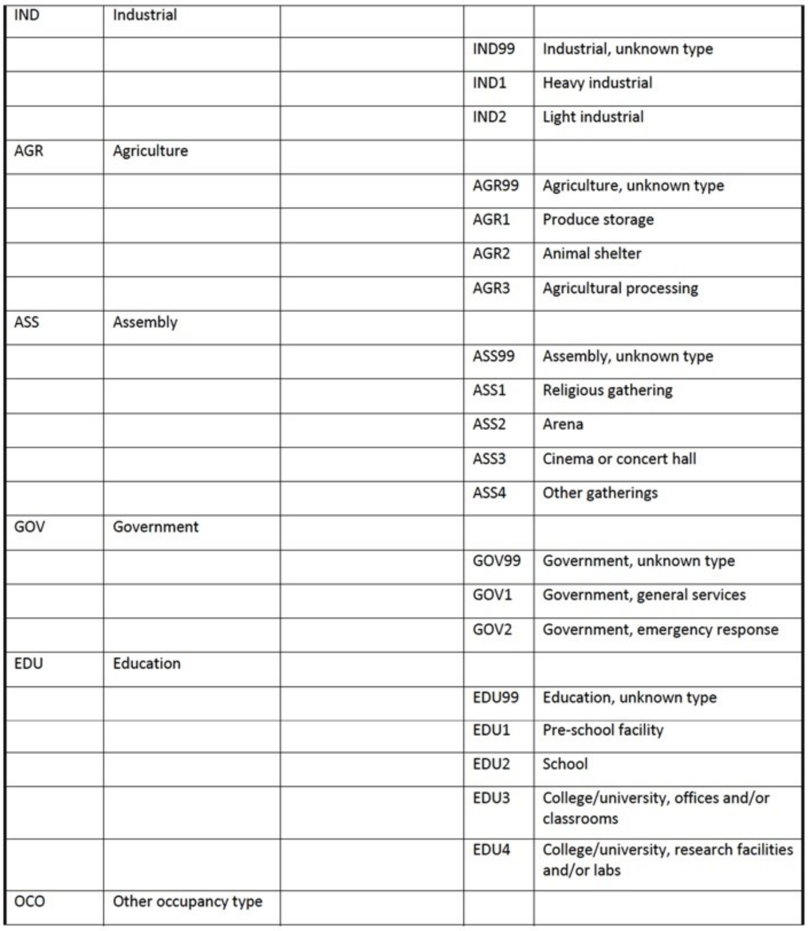


## 10.2 GEM taxonomy

The Global Exposure Model (GEM) has developed a building taxonomy to describe and classify buildings in a uniform manner as a key step towards assessing their seismic risk. Within the 13 building 'attributes', the occupancy features are following reported.



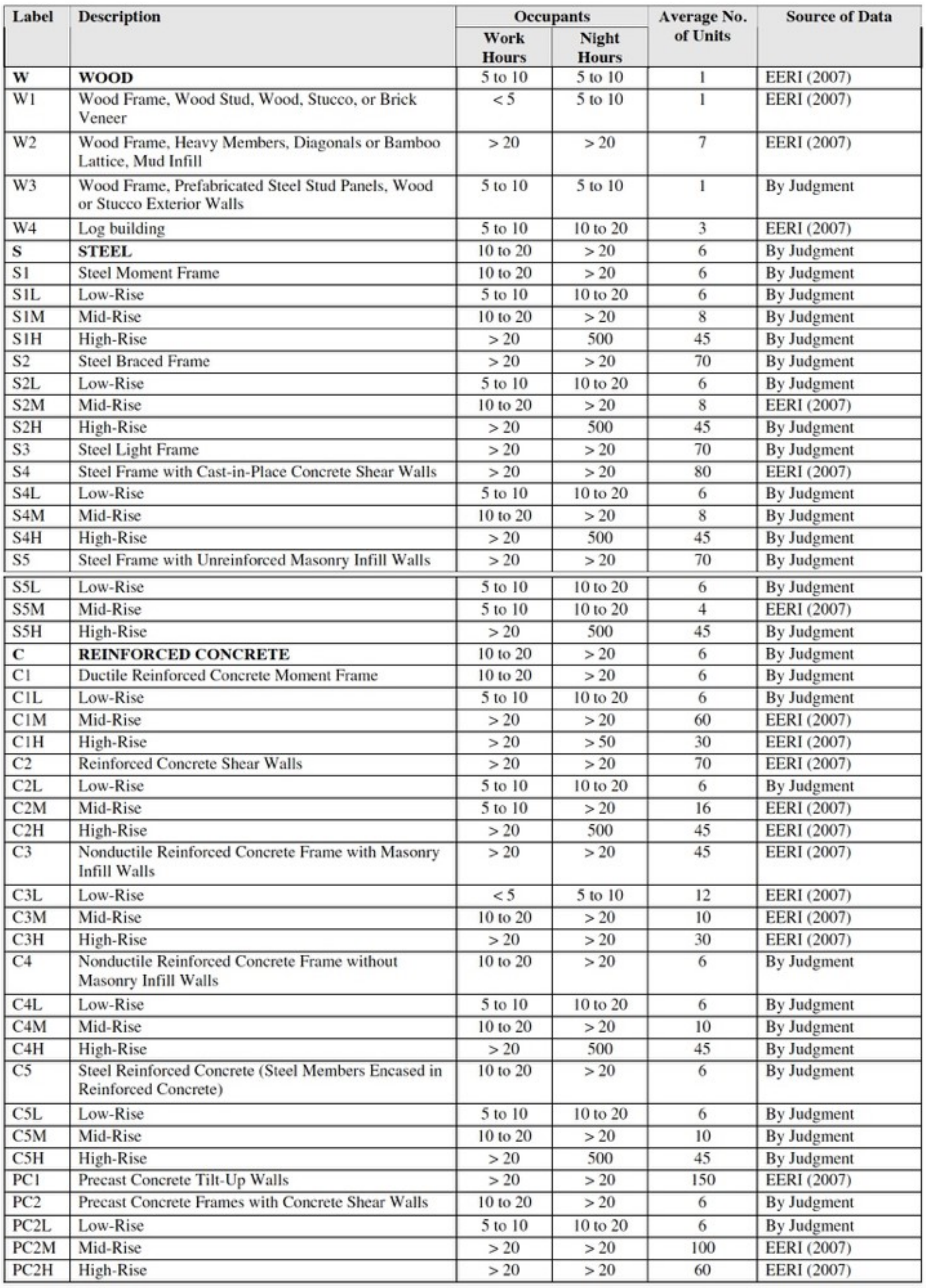
| ID | Level 1 (L1) | | ID | Level 2 (L2) |
|---|---|---|---|---|
| | Building occupancy class - general | Definition | | Building occupancy class - detail |
| Attribute_ Type_Code | OCCUPCY | | | OCCUPCY_DT |
| OC99 | Unknown occupancy type | | | |
| RES | Residential | | | |
| | | | RES99 | Residential, unknown type |
| | | | RES1 | Single dwelling |
| | | | RES2 | Multi-unit, unknown type |
| | | | RES2A | 2 Units (duplex) |
| | | | RES2B | 3-4 Units |
| | | | RES2C | 5-9 Units |
| | | | RES2D | 10-19 Units |
| | | | RES2E | 20-49 Units |
| | | | RES2F | 50+ Units |
| | | | RES3 | Temporary lodging |
| | | | RES4 | Institutional housing |
| | | | RES5 | Mobile home |
| | | | RES6 | Informal housing |
| COM | Commercial and public | | | |
| | | | COM99 | Commercial and public, unknown type |
| | | | COM1 | Retail trade |
| | | | COM2 | Wholesale trade and storage (warehouse) |
| Attribute_ Type_Code | OCCUPCY | | | OCCUPCY_DT |
| | | | COM3 | Offices, professional/technical services |
| | | | COM4 | Hospital/medical clinic |
| | | | COM5 | Entertainment |
| | | | COM6 | Public building |
| | | | COM7 | Covered parking garage |
| | | | COM8 | Bus station |
| | | | COM9 | Railway station |
| | | | COM10 | Airport |
| | | | COM11 | Recreation and leisure |
| MIX | Mixed use | | | |
| | | | MIX99 | Mixed, unknown type |
| | | | MIX1 | Mostly residential and commercial |
| | | | MIX2 | Mostly commercial and residential |
| | | | MIX3 | Mostly commercial and industrial |
| | | | MIX4 | Mostly residential and industrial |
| | | | MIX5 | Mostly industrial and commercial |
| | | | MIX6 | Mostly industrial and residential |



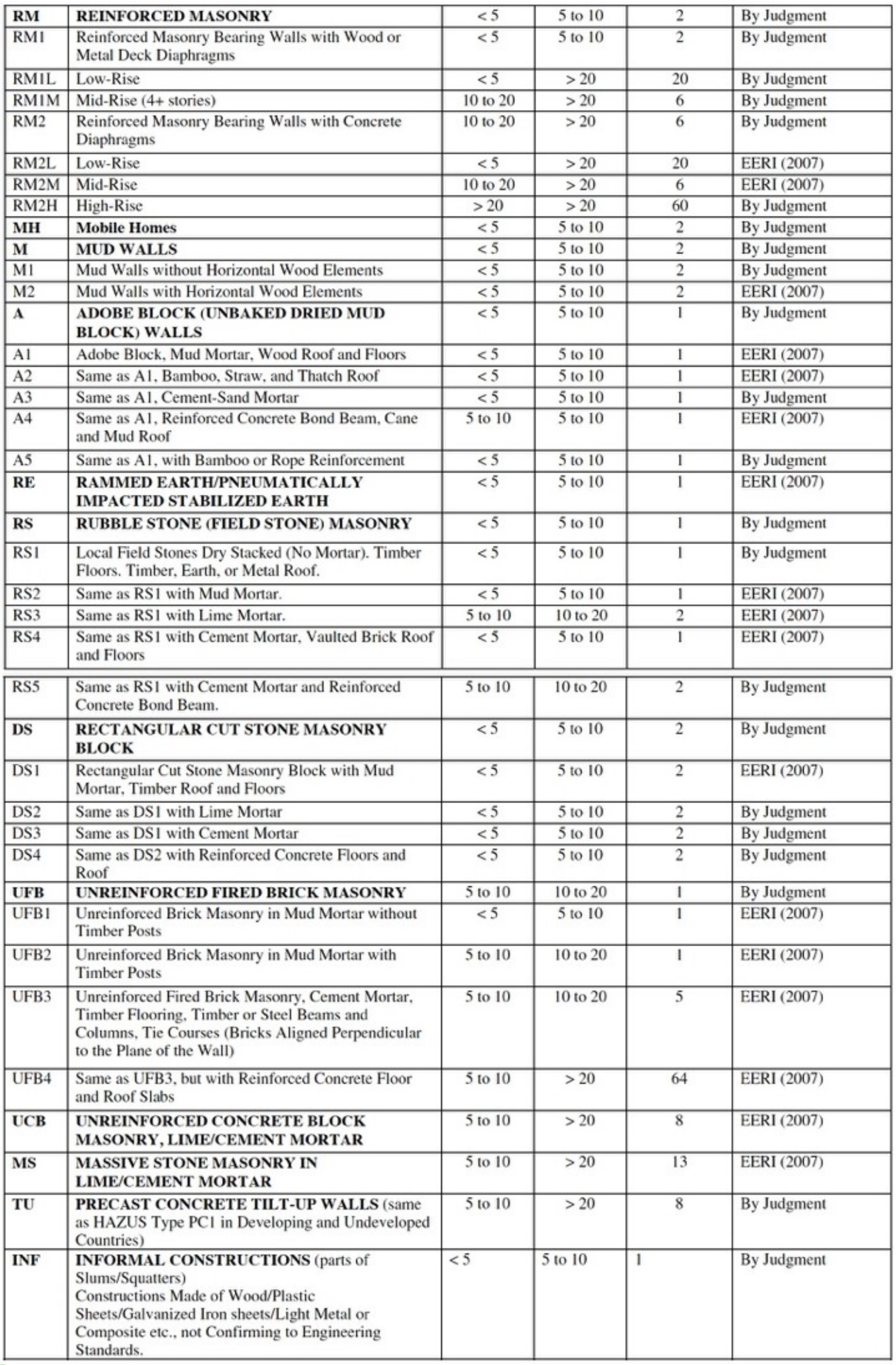
| | | | | |
|---|---|---|---|---|
| IND | Industrial | | | |
| | | | IND99 | Industrial, unknown type |
| | | | IND1 | Heavy industrial |
| | | | IND2 | Light industrial |
| AGR | Agriculture | | | |
| | | | AGR99 | Agriculture, unknown type |
| | | | AGR1 | Produce storage |
| | | | AGR2 | Animal shelter |
| | | | AGR3 | Agricultural processing |
| ASS | Assembly | | | |
| | | | ASS99 | Assembly, unknown type |
| | | | ASS1 | Religious gathering |
| | | | ASS2 | Arena |
| | | | ASS3 | Cinema or concert hall |
| | | | ASS4 | Other gatherings |
| GOV | Government | | | |
| | | | GOV99 | Government, unknown type |
| | | | GOV1 | Government, general services |
| | | | GOV2 | Government, emergency response |
| EDU | Education | | | |
| | | | EDU99 | Education, unknown type |
| | | | EDU1 | Pre-school facility |
| | | | EDU2 | School |
| | | | EDU3 | College/university, offices and/or classrooms |
| | | | EDU4 | College/university, research facilities and/or labs |
| OCO | Other occupancy type | | | |

### 10.3 PAGER taxonomy (Jaiswal and Wald 2008)

The USGS (U.S. Geological Survey), within PAGER project (Prompt Assessment of Global Earthquakes for Response) provide a building-specific inventory estimating the average occupancy (day and night) and average number of units within each model building type.



| Label | Description | Occupants | | Average No. of Units | Source of Data |
|---|---|---|---|---|---|
| | | Work Hours | Night Hours | | |
| **W** | **WOOD** | 5 to 10 | 5 to 10 | 1 | EERI (2007) |
| W1 | Wood Frame, Wood Stud, Wood, Stucco, or Brick Veneer | < 5 | 5 to 10 | 1 | EERI (2007) |
| W2 | Wood Frame, Heavy Members, Diagonals or Bamboo Lattice, Mud Infill | > 20 | > 20 | 7 | EERI (2007) |
| W3 | Wood Frame, Prefabricated Steel Stud Panels, Wood or Stucco Exterior Walls | 5 to 10 | 5 to 10 | 1 | By Judgment |
| W4 | Log building | 5 to 10 | 10 to 20 | 3 | EERI (2007) |
| **S** | **STEEL** | 10 to 20 | > 20 | 6 | By Judgment |
| S1 | Steel Moment Frame | 10 to 20 | > 20 | 6 | By Judgment |
| S1L | Low-Rise | 5 to 10 | 10 to 20 | 6 | By Judgment |
| S1M | Mid-Rise | 10 to 20 | > 20 | 8 | By Judgment |
| S1H | High-Rise | > 20 | 500 | 45 | By Judgment |
| S2 | Steel Braced Frame | > 20 | > 20 | 70 | By Judgment |
| S2L | Low-Rise | 5 to 10 | 10 to 20 | 6 | By Judgment |
| S2M | Mid-Rise | 10 to 20 | > 20 | 8 | EERI (2007) |
| S2H | High-Rise | > 20 | 500 | 45 | By Judgment |
| S3 | Steel Light Frame | > 20 | > 20 | 70 | By Judgment |
| S4 | Steel Frame with Cast-in-Place Concrete Shear Walls | > 20 | > 20 | 80 | EERI (2007) |
| S4L | Low-Rise | 5 to 10 | 10 to 20 | 6 | By Judgment |
| S4M | Mid-Rise | 10 to 20 | > 20 | 8 | By Judgment |
| S4H | High-Rise | > 20 | 500 | 45 | By Judgment |
| S5 | Steel Frame with Unreinforced Masonry Infill Walls | > 20 | > 20 | 70 | By Judgment |
| S5L | Low-Rise | 5 to 10 | 10 to 20 | 6 | By Judgment |
| S5M | Mid-Rise | 5 to 10 | 10 to 20 | 4 | EERI (2007) |
| S5H | High-Rise | > 20 | 500 | 45 | By Judgment |
| **C** | **REINFORCED CONCRETE** | 10 to 20 | > 20 | 6 | By Judgment |
| C1 | Ductile Reinforced Concrete Moment Frame | 10 to 20 | > 20 | 6 | By Judgment |
| C1L | Low-Rise | 5 to 10 | 10 to 20 | 6 | By Judgment |
| C1M | Mid-Rise | > 20 | > 20 | 60 | EERI (2007) |
| C1H | High-Rise | > 20 | > 50 | 30 | EERI (2007) |
| C2 | Reinforced Concrete Shear Walls | > 20 | > 20 | 70 | EERI (2007) |
| C2L | Low-Rise | 5 to 10 | 10 to 20 | 6 | By Judgment |
| C2M | Mid-Rise | 5 to 10 | > 20 | 16 | EERI (2007) |
| C2H | High-Rise | > 20 | 500 | 45 | EERI (2007) |
| C3 | Nonductile Reinforced Concrete Frame with Masonry Infill Walls | > 20 | > 20 | 45 | EERI (2007) |
| C3L | Low-Rise | < 5 | 5 to 10 | 12 | EERI (2007) |
| C3M | Mid-Rise | 10 to 20 | > 20 | 10 | EERI (2007) |
| C3H | High-Rise | > 20 | > 20 | 30 | EERI (2007) |
| C4 | Nonductile Reinforced Concrete Frame without Masonry Infill Walls | 10 to 20 | > 20 | 6 | By Judgment |
| C4L | Low-Rise | 5 to 10 | 10 to 20 | 6 | By Judgment |
| C4M | Mid-Rise | 10 to 20 | > 20 | 10 | By Judgment |
| C4H | High-Rise | > 20 | 500 | 45 | By Judgment |
| C5 | Steel Reinforced Concrete (Steel Members Encased in Reinforced Concrete) | 10 to 20 | > 20 | 6 | By Judgment |
| C5L | Low-Rise | 5 to 10 | 10 to 20 | 6 | By Judgment |
| C5M | Mid-Rise | 10 to 20 | > 20 | 10 | By Judgment |
| C5H | High-Rise | > 20 | 500 | 45 | By Judgment |
| PC1 | Precast Concrete Tilt-Up Walls | > 20 | > 20 | 150 | EERI (2007) |
| PC2 | Precast Concrete Frames with Concrete Shear Walls | 10 to 20 | > 20 | 6 | By Judgment |
| PC2L | Low-Rise | 5 to 10 | 10 to 20 | 6 | By Judgment |
| PC2M | Mid-Rise | > 20 | > 20 | 100 | EERI (2007) |
| PC2H | High-Rise | > 20 | > 20 | 60 | EERI (2007) |



| | | | | | |
|---|---|---|---|---|---|
| **RM** | **REINFORCED MASONRY** | < 5 | 5 to 10 | 2 | By Judgment |
| RM1 | Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms | < 5 | 5 to 10 | 2 | By Judgment |
| RM1L | Low-Rise | < 5 | > 20 | 20 | By Judgment |
| RM1M | Mid-Rise (4+ stories) | 10 to 20 | > 20 | 6 | By Judgment |
| RM2 | Reinforced Masonry Bearing Walls with Concrete Diaphragms | 10 to 20 | > 20 | 6 | By Judgment |
| RM2L | Low-Rise | < 5 | > 20 | 20 | EERI (2007) |
| RM2M | Mid-Rise | 10 to 20 | > 20 | 6 | EERI (2007) |
| RM2H | High-Rise | > 20 | > 20 | 60 | By Judgment |
| **MH** | **Mobile Homes** | < 5 | 5 to 10 | 2 | By Judgment |
| **M** | **MUD WALLS** | < 5 | 5 to 10 | 2 | By Judgment |
| M1 | Mud Walls without Horizontal Wood Elements | < 5 | 5 to 10 | 2 | By Judgment |
| M2 | Mud Walls with Horizontal Wood Elements | < 5 | 5 to 10 | 2 | EERI (2007) |
| **A** | **ADOBE BLOCK (UNBAKED DRIED MUD BLOCK) WALLS** | < 5 | 5 to 10 | 1 | By Judgment |
| A1 | Adobe Block, Mud Mortar, Wood Roof and Floors | < 5 | 5 to 10 | 1 | EERI (2007) |
| A2 | Same as A1, Bamboo, Straw, and Thatch Roof | < 5 | 5 to 10 | 1 | EERI (2007) |
| A3 | Same as A1, Cement-Sand Mortar | < 5 | 5 to 10 | 1 | By Judgment |
| A4 | Same as A1, Reinforced Concrete Bond Beam, Cane and Mud Roof | 5 to 10 | 5 to 10 | 1 | EERI (2007) |
| A5 | Same as A1, with Bamboo or Rope Reinforcement | < 5 | 5 to 10 | 1 | By Judgment |
| **RE** | **RAMMED EARTH/PNEUMATICALLY IMPACTED STABILIZED EARTH** | < 5 | 5 to 10 | 1 | EERI (2007) |
| **RS** | **RUBBLE STONE (FIELD STONE) MASONRY** | < 5 | 5 to 10 | 1 | By Judgment |
| RS1 | Local Field Stones Dry Stacked (No Mortar). Timber Floors. Timber, Earth, or Metal Roof. | < 5 | 5 to 10 | 1 | By Judgment |
| RS2 | Same as RS1 with Mud Mortar. | < 5 | 5 to 10 | 1 | EERI (2007) |
| RS3 | Same as RS1 with Lime Mortar. | 5 to 10 | 10 to 20 | 2 | EERI (2007) |
| RS4 | Same as RS1 with Cement Mortar, Vaulted Brick Roof and Floors | < 5 | 5 to 10 | 1 | EERI (2007) |
| RS5 | Same as RS1 with Cement Mortar and Reinforced Concrete Bond Beam. | 5 to 10 | 10 to 20 | 2 | By Judgment |
| **DS** | **RECTANGULAR CUT STONE MASONRY BLOCK** | < 5 | 5 to 10 | 2 | By Judgment |
| DS1 | Rectangular Cut Stone Masonry Block with Mud Mortar, Timber Roof and Floors | < 5 | 5 to 10 | 2 | EERI (2007) |
| DS2 | Same as DS1 with Lime Mortar | < 5 | 5 to 10 | 2 | By Judgment |
| DS3 | Same as DS1 with Cement Mortar | < 5 | 5 to 10 | 2 | By Judgment |
| DS4 | Same as DS2 with Reinforced Concrete Floors and Roof | < 5 | 5 to 10 | 2 | By Judgment |
| **UFB** | **UNREINFORCED FIRED BRICK MASONRY** | 5 to 10 | 10 to 20 | 1 | By Judgment |
| UFB1 | Unreinforced Brick Masonry in Mud Mortar without Timber Posts | < 5 | 5 to 10 | 1 | EERI (2007) |
| UFB2 | Unreinforced Brick Masonry in Mud Mortar with Timber Posts | 5 to 10 | 10 to 20 | 1 | EERI (2007) |
| UFB3 | Unreinforced Fired Brick Masonry, Cement Mortar, Timber Flooring, Timber or Steel Beams and Columns, Tie Courses (Bricks Aligned Perpendicular to the Plane of the Wall) | 5 to 10 | 10 to 20 | 5 | EERI (2007) |
| UFB4 | Same as UFB3, but with Reinforced Concrete Floor and Roof Slabs | 5 to 10 | > 20 | 64 | EERI (2007) |
| **UCB** | **UNREINFORCED CONCRETE BLOCK MASONRY, LIME/CEMENT MORTAR** | 5 to 10 | > 20 | 8 | EERI (2007) |
| **MS** | **MASSIVE STONE MASONRY IN LIME/CEMENT MORTAR** | 5 to 10 | > 20 | 13 | EERI (2007) |
| **TU** | **PRECAST CONCRETE TILT-UP WALLS** (same as HAZUS Type PC1 in Developing and Undeveloped Countries) | 5 to 10 | > 20 | 8 | By Judgment |
| **INF** | **INFORMAL CONSTRUCTIONS** (parts of Slums/Squatters)<br>Constructions Made of Wood/Plastic Sheets/Galvanized Iron sheets/Light Metal or Composite etc., not Confirming to Engineering Standards. | < 5 | 5 to 10 | 1 | By Judgment |

### 10.4 UNI 10339:1995 – crowding index per m2

This table provides crowding index referring to such building functions typologies. The indices explain the amount of people per one m$^2$ of surface. They must not be mandatory but, if real data are not available, these values are useful as reference for projects. They are not referred to transit zones.

| BUILDING CATEGORY | CROWDING INDEX |
|---|---|
| BUILDINGS USED FOR RESIDENTIAL PURPOSES AND SIMILAR | |
| PRIVATE DWELLING | |
| - living room, bedroom | 0,04 |
| SEMINARY, COLLAGE, PENITENTIARY, BARRACKS | |
| - living room | 0,20 |
| - conference room | 0,60 |
| - dorm room | 0,10 |
| - bedroom | 0,05 |
| HOTELS | |
| - hall, living room | 0,20 |
| - conference room (small) | 0,60 |
| - bedroom | 0,05 |
| BUILDINGS FOR OFFICES AND SIMILAR | |
| - single office | 0,06 |
| - open space office | 0,12 |
| - meeting room | 0,60 |
| HOSPITALS, CLINICS AND SIMILAR | |
| - critical care rooms | 0,08 |
| - sterile rooms | 0,08 |
| - medical office | 0,05 |
| - clinic | 0,12 |
| BUILDINGS USED BY ASSOCIATIONS, FOR RELIGIOUS PURPOSES AND FOR RECREATIONAL ACTIVITIES | |
| THEATRE, CONFERENCE HALL, CINEMA | |
| - rooms | 1,50 |
| - hall, ticket office | 0,20 |
| - waiting room | 1,00 |
| MUSEUMS, LIBRARY, RELIGIOUS PLACE | |
| - rooms | 0,30 |
| - religious rooms | 0,80 |
| BAR, RESTAURANTS, CLUB | |
| - bar | 0,80 |

| | |
|---|---|
| - restaurant room | 0,60 |
| - club | 1,00 |
| COMMERCIAL BUILDINGS AND SIMILAR | |
| - shopping centre | 0,25 |
| - shops (grocery, clothes, shoes, furniture) | 0,10 |
| - beauty shops, pharmacy, public and bank office | 0,20 |
| SPORTS FACILITIES AND SIMILAR | |
| - swimming pool | 0,30 |
| - sauna | 0,50 |
| - soccer field | 0,20 |
| - bleachers | 1,50 |
| - bowling | 0,60 |
| BUILDINGS FOR SCHOOL-RELATED ACTIVITIES | |
| - kindergarten | 0,40 |
| - high school | 0,45 |
| - university | 0,60 |
| - laboratory | 0,30 |

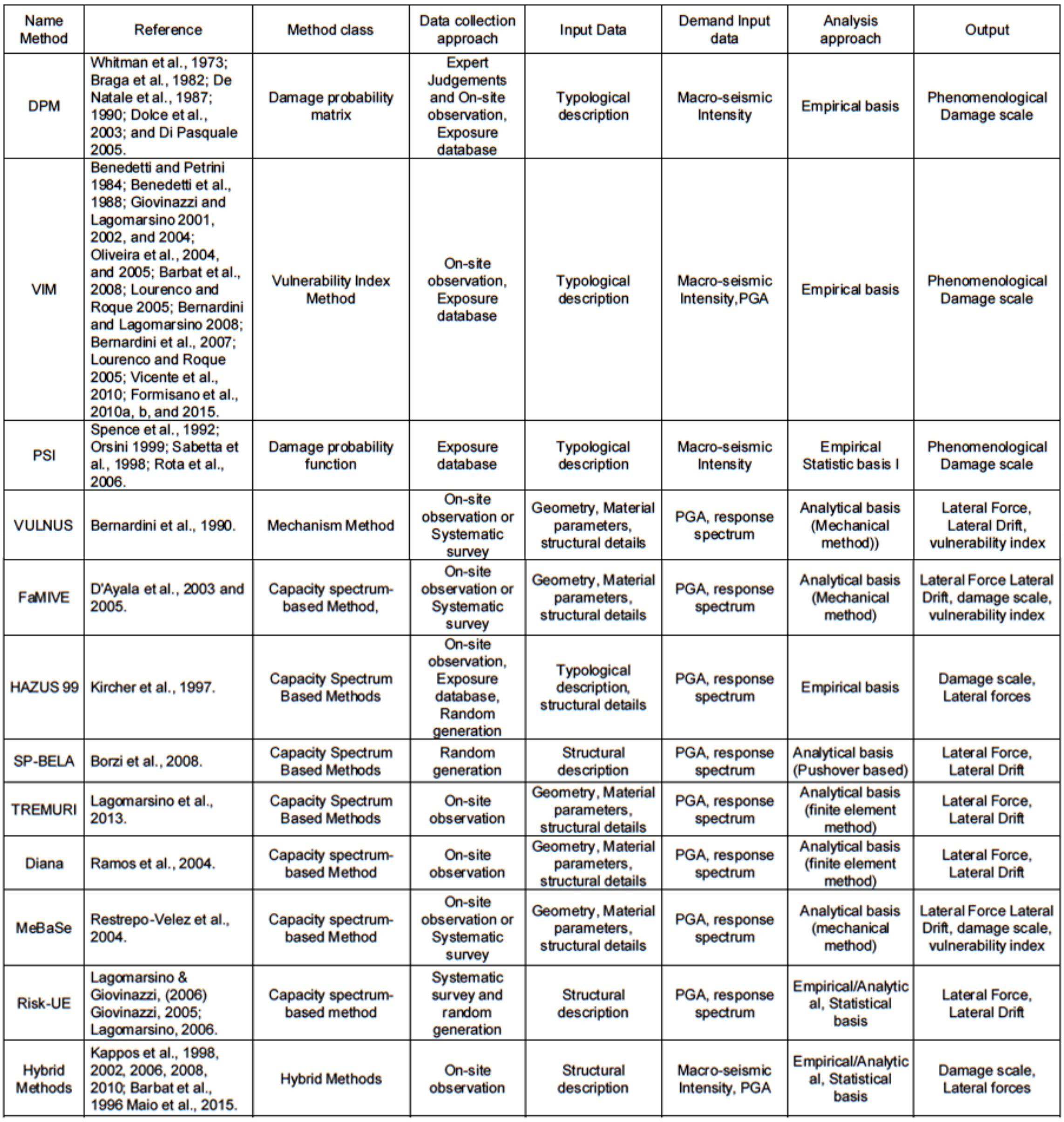
### 10.5 Fire Safety Code (D.M. 3.8.2015 §S.4.6.2) – crowding index (person/m2) or criteria

This table provides crowding index or criteria referring to several building functions and activities. They are expressed in terms of the maximum density permitted.

| BUILDING CATEGORY | CROWDING INDEX OR CRITERIA |
|---|---|
| Entertainment public space (without seats)<br>Space for exhibition, temporary events, demonstrations | 1,2 |
| Restaurant area | 0,7 |
| Area for educational activities or laboratory (without seats)<br>Waiting area<br>Public office<br>Small business, retail shop (grocery, etc.) | 0,4 |
| Medium business or large retail shop<br>Business activities and shop (excluded grocery)<br>Library, reading room, archives | 0,2 |
| Clinic<br>Private office<br>Store, non-retail shop<br>Small business activities and specific retail shop (excluded grocery) | 0,1 |
| Residential dwelling | 0,05 |
| Parking | 2 person per car |
| Care rooms | 1 person with 2 accompanying persons |
| Area for seats or beds (conference room, educational room, dorm room, etc.) | N. of seats or beds |
| Other activities | N. of users<br>(staff + visitors) |

## 10.6 Summary of vulnerability assessment methodologies (Novelli 2017)

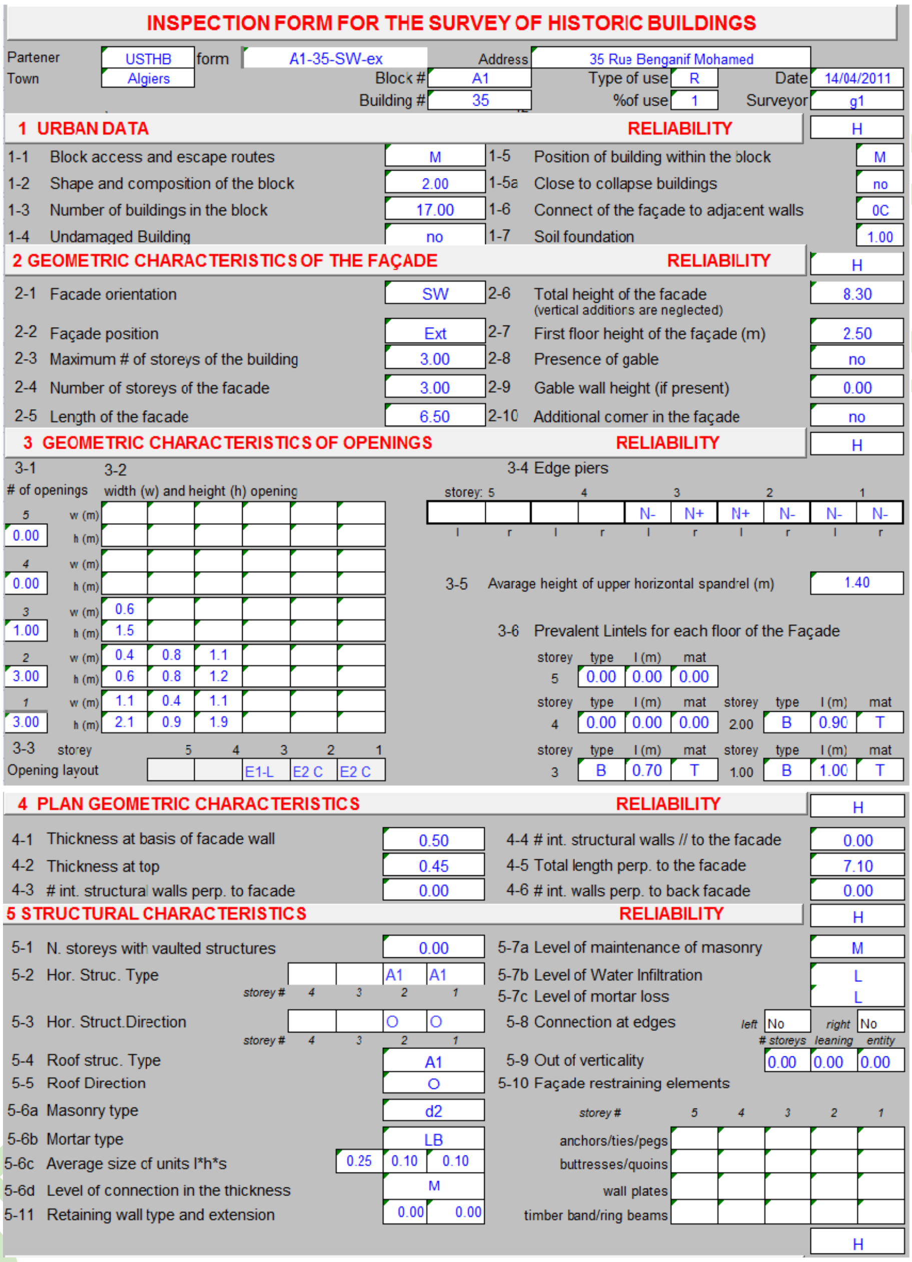
The table summarize the main methodologies developed for the seismic vulnerability assessment



| Name Method | Reference | Method class | Data collection approach | Input Data | Demand Input data | Analysis approach | Output |
|---|---|---|---|---|---|---|---|
| DPM | Whitman et al., 1973; Braga et al., 1982; De Natale et al., 1987; 1990; Dolce et al., 2003; and Di Pasquale 2005. | Damage probability matrix | Expert Judgements and On-site observation, Exposure database | Typological description | Macro-seismic Intensity | Empirical basis | Phenomenological Damage scale |
| VIM | Benedetti and Petrini 1984; Benedetti et al., 1988; Giovinazzi and Lagomarsino 2001, 2002, and 2004; Oliveira et al., 2004, and 2005; Barbat et al., 2008; Lourenco and Roque 2005; Bernardini and Lagomarsino 2008; Bernardini et al., 2007; Lourenco and Roque 2005; Vicente et al., 2010; Formisano et al., 2010a, b, and 2015. | Vulnerability Index Method | On-site observation, Exposure database | Typological description | Macro-seismic Intensity,PGA | Empirical basis | Phenomenological Damage scale |
| PSI | Spence et al., 1992; Orsini 1999; Sabetta et al., 1998; Rota et al., 2006. | Damage probability function | Exposure database | Typological description | Macro-seismic Intensity | Empirical Statistic basis I | Phenomenological Damage scale |
| VULNUS | Bernardini et al., 1990. | Mechanism Method | On-site observation or Systematic survey | Geometry, Material parameters, structural details | PGA, response spectrum | Analytical basis (Mechanical method)) | Lateral Force, Lateral Drift, vulnerability index |
| FaMIVE | D'Ayala et al., 2003 and 2005. | Capacity spectrum-based Method, | On-site observation or Systematic survey | Geometry, Material parameters, structural details | PGA, response spectrum | Analytical basis (Mechanical method) | Lateral Force Lateral Drift, damage scale, vulnerability index |
| HAZUS 99 | Kircher et al., 1997. | Capacity Spectrum Based Methods | On-site observation, Exposure database, Random generation | Typological description, structural details | PGA, response spectrum | Empirical basis | Damage scale, Lateral forces |
| SP-BELA | Borzi et al., 2008. | Capacity Spectrum Based Methods | Random generation | Structural description | PGA, response spectrum | Analytical basis (Pushover based) | Lateral Force, Lateral Drift |
| TREMURI | Lagomarsino et al., 2013. | Capacity Spectrum Based Methods | On-site observation | Geometry, Material parameters, structural details | PGA, response spectrum | Analytical basis (finite element method) | Lateral Force, Lateral Drift |
| Diana | Ramos et al., 2004. | Capacity spectrum-based Method | On-site observation | Geometry, Material parameters, structural details | PGA, response spectrum | Analytical basis (finite element method) | Lateral Force, Lateral Drift |
| MeBaSe | Restrepo-Velez et al., 2004. | Capacity spectrum-based Method | On-site observation or Systematic survey | Geometry, Material parameters, structural details | PGA, response spectrum | Analytical basis (mechanical method) | Lateral Force Lateral Drift, damage scale, vulnerability index |
| Risk-UE | Lagomarsino & Giovinazzi, (2006) Giovinazzi, 2005; Lagomarsino, 2006. | Capacity spectrum-based method | Systematic survey and random generation | Structural description | PGA, response spectrum | Empirical/Analytical, Statistical basis | Lateral Force, Lateral Drift |
| Hybrid Methods | Kappos et al., 1998, 2002, 2006, 2008, 2010; Barbat et al., 1996 Maio et al., 2015. | Hybrid Methods | On-site observation | Structural description | Macro-seismic Intensity, PGA | Empirical/Analytical, Statistical basis | Damage scale, Lateral forces |

## 10.7 Inspection form of FaMIVE (Novelli 2017)

The following form is a spreadsheet developed within FaMIVE method for assessing the vulnerability and the damage state of building.



**INSPECTION FORM FOR THE SURVEY OF HISTORIC BUILDINGS**

Partener: USTHB
form: A1-35-SW-ex
Address: 35 Rue Benganif Mohamed
Town: Algiers
Block #: A1
Type of use: R
Date: 14/04/2011
Building #: 35
%of use: 1
Surveyor: g1

**1 URBAN DATA** — RELIABILITY: H

| | | | | | |
|---|---|---|---|---|---|
| 1-1 | Block access and escape routes | M | 1-5 | Position of building within the block | M |
| 1-2 | Shape and composition of the block | 2.00 | 1-5a | Close to collapse buildings | no |
| 1-3 | Number of buildings in the block | 17.00 | 1-6 | Connect of the façade to adjacent walls | 0C |
| 1-4 | Undamaged Building | no | 1-7 | Soil foundation | 1.00 |

**2 GEOMETRIC CHARACTERISTICS OF THE FAÇADE** — RELIABILITY: H

| | | | | | |
|---|---|---|---|---|---|
| 2-1 | Facade orientation | SW | 2-6 | Total height of the facade<br>(vertical additions are neglected) | 8.30 |
| 2-2 | Façade position | Ext | 2-7 | First floor height of the façade (m) | 2.50 |
| 2-3 | Maximum # of storeys of the building | 3.00 | 2-8 | Presence of gable | no |
| 2-4 | Number of storeys of the facade | 3.00 | 2-9 | Gable wall height (if present) | 0.00 |
| 2-5 | Length of the facade | 6.50 | 2-10 | Additional corner in the façade | no |

**3 GEOMETRIC CHARACTERISTICS OF OPENINGS** — RELIABILITY: H

3-1 # of openings; 3-2 width (w) and height (h) opening

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 5 | 0.00 | w (m) | | | | | | |
| | | h (m) | | | | | | |
| 4 | 0.00 | w (m) | | | | | | |
| | | h (m) | | | | | | |
| 3 | 1.00 | w (m) | 0.6 | | | | | |
| | | h (m) | 1.5 | | | | | |
| 2 | 3.00 | w (m) | 0.4 | 0.8 | 1.1 | | | |
| | | h (m) | 0.6 | 0.8 | 1.2 | | | |
| 1 | 3.00 | w (m) | 1.1 | 0.4 | 1.1 | | | |
| | | h (m) | 2.1 | 0.9 | 1.9 | | | |

3-3 Opening layout

| storey | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|
| Opening layout | | | E1-L | E2 C | E2 C |

3-4 Edge piers

| storey: | 5 | | 4 | | 3 | | 2 | | 1 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | N- | N+ | N+ | N- | N- | N- |
| | l | r | l | r | l | r | l | r | l | r |

3-5 Avarage height of upper horizontal spandrel (m): 1.40

3-6 Prevalent Lintels for each floor of the Façade

| storey | type | l (m) | mat | storey | type | l (m) | mat |
|---|---|---|---|---|---|---|---|
| 5 | 0.00 | 0.00 | 0.00 | | | | |
| 4 | 0.00 | 0.00 | 0.00 | 2.00 | B | 0.90 | T |
| 3 | B | 0.70 | T | 1.00 | B | 1.00 | T |

**4 PLAN GEOMETRIC CHARACTERISTICS** — RELIABILITY: H

| | | | | | |
|---|---|---|---|---|---|
| 4-1 | Thickness at basis of facade wall | 0.50 | 4-4 | # int. structural walls // to the facade | 0.00 |
| 4-2 | Thickness at top | 0.45 | 4-5 | Total length perp. to the facade | 7.10 |
| 4-3 | # int. structural walls perp. to facade | 0.00 | 4-6 | # int. walls perp. to back facade | 0.00 |

**5 STRUCTURAL CHARACTERISTICS** — RELIABILITY: H

5-1 N. storeys with vaulted structures: 0.00

| | storey # 4 | 3 | 2 | 1 |
|---|---|---|---|---|
| 5-2 Hor. Struc. Type | | | A1 | A1 |
| 5-3 Hor. Struct.Direction | | | O | O |

5-4 Roof struc. Type: A1
5-5 Roof Direction: O
5-6a Masonry type: d2
5-6b Mortar type: LB
5-6c Average size of units l*h*s: 0.25 | 0.10 | 0.10
5-6d Level of connection in the thickness: M
5-11 Retaining wall type and extension: 0.00 | 0.00

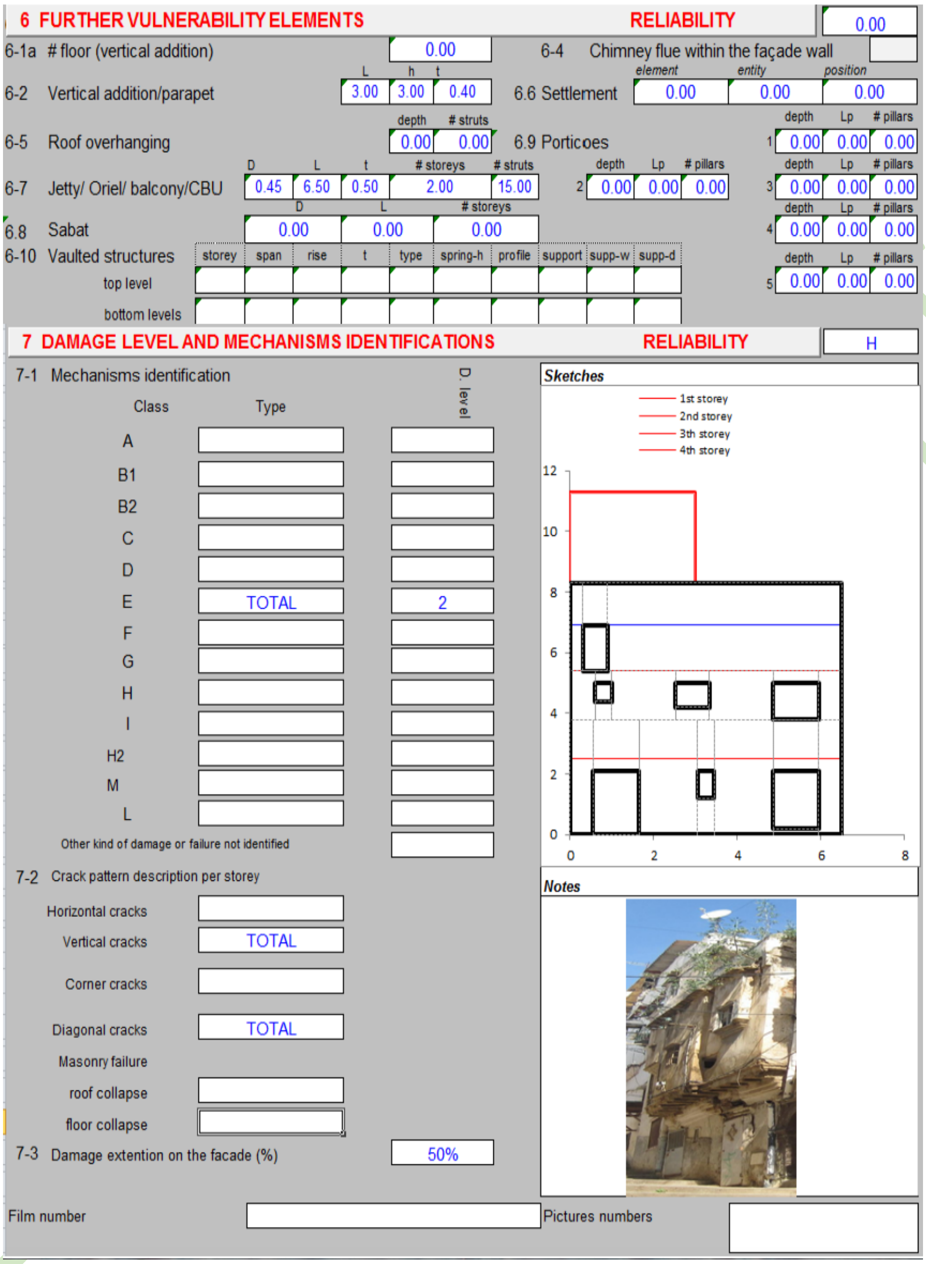
5-7a Level of maintenance of masonry: M
5-7b Level of Water Infiltration: L
5-7c Level of mortar loss: L
5-8 Connection at edges: left No; right No

| | # storeys | leaning | entity |
|---|---|---|---|
| 5-9 Out of verticality | 0.00 | 0.00 | 0.00 |

5-10 Façade restraining elements

| storey # | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|
| anchors/ties/pegs | | | | | |
| buttresses/quoins | | | | | |
| wall plates | | | | | |
| timber band/ring beams | | | | | |

H



**6 FURTHER VULNERABILITY ELEMENTS** RELIABILITY 0.00

6-1a # floor (vertical addition) 0.00

6-4 Chimney flue within the façade wall

| | L | h | t |
|---|---|---|---|
| 6-2 Vertical addition/parapet | 3.00 | 3.00 | 0.40 |

| | element | entity | position |
|---|---|---|---|
| 6.6 Settlement | 0.00 | 0.00 | 0.00 |

| | depth | # struts |
|---|---|---|
| 6-5 Roof overhanging | 0.00 | 0.00 |

| | D | L | t | # storeys | # struts |
|---|---|---|---|---|---|
| 6-7 Jetty/ Oriel/ balcony/CBU | 0.45 | 6.50 | 0.50 | 2.00 | 15.00 |

| | D | L | # storeys |
|---|---|---|---|
| 6.8 Sabat | 0.00 | 0.00 | 0.00 |

6.9 Porticoes

| | depth | Lp | # pillars |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 0.00 | 0.00 | 0.00 |
| 3 | 0.00 | 0.00 | 0.00 |
| 4 | 0.00 | 0.00 | 0.00 |
| 5 | 0.00 | 0.00 | 0.00 |

| 6-10 Vaulted structures | storey | span | rise | t | type | spring-h | profile | support | supp-w | supp-d |
|---|---|---|---|---|---|---|---|---|---|---|
| top level | | | | | | | | | | |
| bottom levels | | | | | | | | | | |

**7 DAMAGE LEVEL AND MECHANISMS IDENTIFICATIONS** RELIABILITY H

7-1 Mechanisms identification

| Class | Type | D. level |
|---|---|---|
| A | | |
| B1 | | |
| B2 | | |
| C | | |
| D | | |
| E | TOTAL | 2 |
| F | | |
| G | | |
| H | | |
| I | | |
| H2 | | |
| M | | |
| L | | |
| Other kind of damage or failure not identified | | |

7-2 Crack pattern description per storey

| | |
|---|---|
| Horizontal cracks | |
| Vertical cracks | TOTAL |
| Corner cracks | |
| Diagonal cracks | TOTAL |
| Masonry failure | |
| roof collapse | |
| floor collapse | |

7-3 Damage extention on the facade (%) 50%

Sketches

Notes

Film number

Pictures numbers

### 10.8 Review of the main vulnerability assessment issues

The following table provide a clear insight of the main issues related to the methodologies discussed (§5.3) in order to outline the completeness of each approach.

| | Giovinazzi, Lagomarsino | Vicente | Ferreira | Quagliarini | Rapone | Formisano | FaMIVE | Mochi, Predari |
|---|---|---|---|---|---|---|---|---|
| **Approach** | VIM<br>Macroseismic | VIM<br>Macroseismic | VIM<br>Macroseismic | VIM<br>Macroseismic | VIM<br>Macroseismic | VIM<br>Macroseismic | Analytical<br>Mechanical | Empirical<br>Mechanical |
| **INPUT** | Construction/ structural characteristics | Construction/ structural characteristics | Construction/ structural characteristics | Construction/ structural characteristics | Construction/ structural characteristics | Construction/ structural characteristics | - Construction characteristics<br>- Failure mechanisms | - Construction characteristics<br>- Failure mechanisms |
| **OUTPUT** | -Vulnerability index/class<br>-Mean damage<br>-Fragility curves | -Vulnerability index/class<br>-Mean damage<br>-Fragility curves | -Vulnerability index/class<br>-Mean damage<br>-Fragility curves | -Vulnerability index/class<br>-Mean damage | -Vulnerability index/class<br>-Mean damage<br>-Fragility curves | -Vulnerability index/class<br>-Mean damage<br>-Fragility curves | - Collapse multipliers<br>- Fragility, capacity curves | -Vulnerability index/class |
| **Hazard measure** | Intensity (EMS-98), spectral response | PGA, Intensity (EMS-98) | PGA, Intensity (EMS-98) | | Intensity (EMS-98), $a_g$ | PGA, Intensity (EMS-98), spectral response | PGA, spectral response | |
| **Historic evolution** | ✓ | | | | | | ( ✓ ) | ✓ |
| **Structural characteristics** (see Tab.1 §5.2) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Interaction between SU** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Masonry quality** | ✓ | ✓ | ✓ | | ( ✓ ) | ✓ | ✓ | ✓ |
| **Failure modes** | | | | | ✓ | | ✓ | ✓ |

## 10.9 EMS-98 damage scale

The classification of damage to masonry buildings developed within the EMS-98 macroseismic scale.

| | |
|---|---|
|  | **Grade 1: Negligible to slight damage**<br>**(no structural damage, slight non-structural damage)**<br>Hair-line cracks in very few walls.<br>Fall of small pieces of plaster only.<br>Fall of loose stones from upper parts of buildings in very few cases. |
|  | **Grade 2: Moderate damage**<br>**(slight structural damage, moderate non-structural damage)**<br>Cracks in many walls.<br>Fall of fairly large pieces of plaster.<br>Partial collapse of chimneys. |
|  | **Grade 3: Substantial to heavy damage**<br>**(moderate structural damage, heavy non-structural damage)**<br>Large and extensive cracks in most walls.<br>Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls). |
|  | **Grade 4: Very heavy damage**<br>**(heavy structural damage, very heavy non-structural damage)**<br>Serious failure of walls; partial structural failure of roofs and floors. |
|  | **Grade 5: Destruction**<br>**(very heavy structural damage)**<br>Total or near total collapse. |

## 10.10 Damage state scale and Damage extent matrix proposed within FaMIVE method (Novelli 2017)

The damage scale provide the damage thresholds as reference within the vulnerability curves developed by FaMIVE, and the relative extent of damage related to the vulnerability index classes.

| Damage State | Description | In-plane failure | Overturning failure |
|---|---|---|---|
| **No damage (ND)** | Hair-line cracks in very few walls, detachment or fall of small pieces of stucco only. Fall of loose stones or bricks from upper parts of buildings |  |  |
| **Light damage (LD)** | Slight cracks in few walls. Detachment or fall of large pieces of stucco. Partial collapse of chimneys, and detachment of few roof tiles |  |  |
| **Severe damage (SD)** | Large and extensive cracks in external façades, and in gable walls, partial detachment between façades and between internal walls and façades, failure of chimneys; fall of roof tiles. |  |  |
| **Near collapse (NC)** | Serious failure in external façades, and gable walls complete detachment between façades and between internal walls and façades, partial structural failure of roof and floors |  |  |
| **Collapse (C)** | Total or near total (more than 50%) failure or crush of external façades, and gable walls, total structural failure of roof and floors |  |  |

| Damage extent (De) | Vulnerability Range | | | |
|---|---|---|---|---|
| | $I_{Vuln,max}$ /6< $I_{Vuln}$ <=$I_{Vuln,max}$ | $I_{Vuln,max}$ /4<= $I_{Vuln}$ < $I_{Vuln,max}$ /6 | $I_{Vuln,max}$ /2<= $I_{Vuln}$ < $I_{Vuln,max}$ /4 | 0= $I_{Vuln}$ < $I_{Vuln,max}$/2 |
| De > 80% of the macroelement (from Near Collapse to Collapse) | VERY HIGH | HIGH | MEDIUM | MEDIUM |
| 40% of the macroelement < De <=80% of the macroelement (from Severe to Near Collapse) | VERY HIGH | HIGH | MEDIUM | LOW |
| 40% of macroelement <De<= No damage (from No Damage to Severe) | HIGH | MEDIUM | LOW | LOW |

## 10.11 Parameters used to determine the Return Period established by NTC2018

The table reports the definition provided by the Italian seismic code (NTC2018) of the two parameters used to calculate the return period (RP).

| **$V_N$ – Nominal period (§2.4.1. NTC2018)**<br>Represents the period (years) during the building must be preserved for the use which is be built. This period depends on the building function and its relevance: | | **$C_U$ – Usage Class (§2.4.2. NTC2018)**<br>Corresponds to the structure value so that takes into account the impacts of possible damage using a usage coefficient $C_U$ : | | | |
|---|---|---|---|---|---|
| **10 years** | Temporal structures | **Class I** | Buildings occasionally used (rural building) | $C_{U\,I}$ | 0,7 |
| **50 years** | Ordinary structures, such as buildings and infrastructure | **Class II** | Buildings with standard functions and regular crowding | $C_{U\,II}$ | 1,0 |
| **100 years** | Relevant and significant structures (strategic buildings and infrastructures) | **Class III** | Buildings with significant crowding and dangerous function (factories) | $C_{U\,III}$ | 1,5 |
| | | **Class IV** | Strategic and public buildings aimed at emergency management | $C_{U\,IV}$ | 2,0 |